ATLAS of Micromorphology of Mineral Alteration and Weathering

Jean E. Delvigne

The Canadian Mineralogist Special Publication 3
ATLAS of Micromorphology of Mineral Alteration and Weathering
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The photomicrograph illustrates some of the most common patterns of weathering observed within partly weathered primary minerals. A subhedral crystal of orthopyroxene is partly weathered to greenish yellow smectite arranged in a subparallel banded texture. The first-formed smectite is developed from transverse fractures; numerous denticulate remnants of orthopyroxene are still preserved within the alteromorph. Further weathering induces the development of iron oxyhydroxides, either by degradation of the previously formed smectite or by direct weathering of the orthopyroxene residues. Further explanations are given in the caption to photomicrographs 141 and 142.
Preamble

The environment has emerged as a major focus of research in the natural sciences. In many universities, for example the one in which I teach, multidisciplinary teams are busy developing new curricula in the environmental sciences to meet the challenges of modern society. Mineralogy is at the forefront in these programs, because of the focus on near-surface interactions involving rocks, soil, water, air and living organisms.

Mineralogists and petrologists in general have an excellent understanding of the way igneous and metamorphic rocks form, at temperatures as high as 1200°C and at pressures representative of the middle or lower crust. On the contrary, by and large, mineralogists and petrologists have a poor grasp of the way rocks and minerals respond to their near-surface environment. Once these rocks begin a trajectory toward the surface as a result of tectonic forces, the rock-forming minerals generally leave their field of stability, and important adjustments set in. Secondary minerals appear, but mineralogical research is fraught with difficulty. The newly formed assemblages commonly are very fine grained, and thus difficult to investigate quantitatively except by high-resolution microbeam techniques. The rocks are fissured, and the geochemical systems involve circulating water; the stage is set for open-system behavior, with all the complexities that an open system entails. The temperature of reaction is so low that non-equilibrium assemblages of minerals are very much the norm.

Each rock-forming mineral has a story to tell. Furthermore, much information about the starting point in these transformations emerges from a study of the rock’s textural attributes. One must simply be shown what to look for in order to recognize the clues. In this book, Jean Delvigne patiently takes the reader along unfamiliar paths. At the beginning of this atlas, the rocks all look very familiar, as the adjustments are incipient. Then, as one progresses through the book, the rocks look less and less familiar, until virtually nothing is left of the original high-temperature assemblages. A non-genetic terminology is developed to facilitate textural classifications and communication of findings. To a student of mineralogy and petrology, the book illustrates the passage from familiar territory to uncharted waters, the field of activity of soil scientists and agronomists. Of course, to the second group, it is the beginning of the book that is less familiar territory. But to both audiences, mineralogy evidently plays a key role and is a common language.

The Mineralogical Association of Canada, in collaboration with ORSTOM, is proud to bring you this Atlas of Micromorphology of Mineral Alteration and Weathering. It represents the distilled pearls of wisdom of a master in the field. I have learned a great deal in working with Jean Delvigne to make this book a reality. I now look at igneous and metamorphic rocks in thin section from a new perspective, and with new insight. I acknowledge the influence of François Soubies, environmental mineralogist and mineral collector extraordinaire, an employee of ORSTOM formerly at the Laboratoire de Minéralogie, Université Paul-Sabatier, in Toulouse. Thanks to him, and to his enthusiasm, I first met the author, and learned about the wealth of information in the completed manuscript that became this book. Vicki Loschiavo helped me to cope with chapters and figure captions, and to deal with competing commitments. I was very fortunate to count on the same creative team that produced our Special Publication Number 1: Pierrette Tremblay, Publicity Coordinator of the Mineralogical Association of Canada, Michel Guay, and Jean-Claude Côté. I hope that whoever is in the audience, soil scientist, clay mineralogist, economic geologist, agronomist, or petrologist, will find here new insight into the multifarious paths that rocks take to adjust to their new surroundings near the Earth’s surface.

Robert F. Martin
Professor, Department of Earth
and Planetary Sciences, McGill University
Editor, The Canadian Mineralogist
In this Atlas of Micromorphology of Mineral Alteration and Weathering, Jean Delvigne provides a comprehensive statement of problems and a summary of present understanding of weathering, applied to some remarkable West African and Brazilian examples. His complete coverage is representative of the petrographic approach in the study of lateritic alterites. The book differs from others in the study of the petrography of weathering by presenting first the rocks, with their inheritance of hydrothermal alteration. Then he describes in great detail the relationship between parent minerals and the products of their weathering. He makes use of abundant and exceptional illustrations of thin sections. This documentation is of paramount importance for students and non-specialists; it allows them to understand the complexity of such near-surface phenomena. The terminology used in this book is simplified for microscopic descriptions. At first glance, it may appear esoteric, but it serves to characterize structures, textures and interrelations among minerals in alterites and soils.

Every method starts with a few simple concepts, proceeds through a period of growth with increasing sophistication, and finally reaches a stage of synthesis, at which point case histories can be discussed and compared. So it is with the geochemistry of weathering. Several important developments in our understanding of this field have occurred in the last few years. But in most instances, geochemists operate “blindly” in that they typically do not take petrographic descriptions into consideration, an approach that can lead to inconsistent inferences. The inconsistencies arise because of the failure to properly observe and understand textural and mineralogical modifications in the microenvironments of weathering profiles. This book thus also should enlighten geochemists working on weathering processes.

A single volume cannot possibly cover all the facets of the complex problems involved. However, with the help of the excellent examples chosen by the author, the book gives a good overview of the main problems of weathering, and specifically provides insight into the way parent minerals weather, the nature of weathering products, and their variability in a vertical profile and in a lateral sequence. In my opinion, this book will serve as a guide to students, geochemists, geologists, soil scientists, geomorphologists, and environmental scientists concerned with the basic concepts and recent trends in research on the processes of weathering, especially in humid tropical areas.

Daniel Nahon
Professor, University of Aix-Marseille III
O VER THE LAST FIFTEEN YEARS, many soil scientists and others working in Geology, Geochemistry and other Earth Sciences seem to have neglected fundamental descriptive work in the field (cartography, detailed descriptions of weathering profiles and of the landscape, accurate location and distribution of their samples), and most of the primary petrographic methods usually employed in the laboratory (e.g., bulk chemical analyses, grain-size analyses and mineral separations). The observation of their samples, at the scale offered by the optical microscope, is often restricted to the study of a few thin sections prepared from selected samples, whose exact and relative position in a profile and landscape has been recorded in a cursory manner only. In fact, young scientists have a strong inclination to proceed directly to the ultramicroscopic scales. Such observations often yield up-to-date results publishable as short papers in the best international journals or presented in international congresses. Few optical photomicrographs are usually presented.

This approach certainly produces many valuable data concerning the details of the processes studied, especially where crystallography, mineralogy, petrology or geochemistry are concerned. However, often, these results cannot be easily integrated in the context of field observations because the number of samples studied is not sufficient, and because the distribution, in the landscape, of the observed variations cannot be easily deduced. The results of the study can be only applied locally or only with very large and hazardous extrapolations.

For this reason, the author has always considered that these “modern” or recently applied methods of observation, at these scales, cannot be performed accurately without the benefit of complete field studies of the selected natural landscape, and without preliminary observations of the samples at a more “human” scale, such as the scale of the thin section observed with the optical microscope. This approach, in which one goes from the larger to the smaller scales, allows the problems raised in the field to be accurately detected, and appropriate samples to be selected for further and more detailed observations and analyses using the most sophisticated techniques.

The preparation of this Atlas of Micromorphology of Mineral Alteration and Weathering has been undertaken in the hope that it will encourage and facilitate observations at the optical scale. Many examples of varied textural and mineralogical patterns are provided and illustrated profusely. This book is written in such a way that it can be understood by and be useful to geographers or agronomists, whose background in and understanding of petrography and mineralogy are usually rather limited. The beauty of the colors and of the natural textures and mineral associations, as observed with the optical microscope, can also encourage these scientists to use this technique. The book illustrates how one can tackle genetic or chronological problems raised by alteration or weathering processes before an attempt is made to resolve all these problems with the help of ultramicroscopic techniques only.

The scope of this book is restricted to the part of micromorphology related to alteration and weathering.
processes. Many books have been published concerning the micromorphology of soils. These books contain sufficient descriptions and illustrations of general micromorphological features, which are not covered here. The scope of this book also is restricted to the illustration of alteration and weathering processes and features. Very few details on the geochemical processes involved are presented. Other books (e.g., Nahon 1991, White & Brantley 1995) give detailed explanations about the geochemical processes and reactions involved in rock weathering and soil genesis.

All the photomicrographs have been made by the author with the help of a LEITZ polarizing microscope equipped with a WILD Photoautomat camera. Except for very old photomicrographs, all the more recent photos have been recorded on KODAK Ektachrome 64T color-reversal film. This uniformity allows a better homogeneity of colors and of enlargements of all the pictures shown throughout the book.

Most samples were collected by the author during his numerous years of research in Zaire (1956-1961; now Democratic Republic of Congo), in Côte d’Ivoire (1962-1976) and in Brazil (1980-1987). Most of the thin sections of these samples were made in the Laboratoire de Pétrographie, Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM), Abidjan, Côte d’Ivoire, either by the author himself (until 1974) or by Claude Hanriot, who has directed the technical part of this Laboratory since 1973.

Some samples and thin sections have been given or cordially lent by other scientists of the ORSTOM group or affiliated with the universities in which the author worked. Where this is the case, the name of the donor is given in the caption of the photomicrograph. Otherwise, samples and thin sections come from the author’s collection. Where possible, the short bibliography includes the works in which these samples or thin sections are described more fully. The general list of references, given at the end of the book, is reduced to a minimum, and concerns only those books, theses and papers in which the micromorphology of products of weathering processes is specially studied and illustrated.

Only six magnifications were used (x1.6, x2.5, x4, x6.3, x10 and x16) for all the photographs in this atlas. Each photograph is printed with the magnification clearly indicated, and with tick marks labeled from A to E and from 1 to 5, so that is is straightforward to refer to a specific area in the photograph. A1 and C3, for example, correspond, respectively, to the upper left corner and to the central area of the photomicrograph. In most cases, the position of the object described in the caption is obvious, and its exact location can be found without reference to a grid intersection. Coordinates thus are not recorded in the caption in most cases. A special color plate is printed in the inside front and back cover, to allow the reader to recall and easily visualize the main types of alteromorphs, whose names are, for the most part, newly coined terms.

The captions also give information about the state of insertion of the polarizing prisms. PPL (plane-polarized light) is used if only the lower polarizing prism is inserted in the pathway of the light; XPL is used where both lower and upper polarizers are inserted and crossed.

The nomenclature of minerals used in this book follows the rules of the International Mineralogical Association (IMA), with one exception. Although the term “hypersthene” has been formally discredited by the IMA (Morimoto 1989), it is retained here strictly for convenience to refer to an orthopyroxene of a composition intermediate between the magnesian and ferrous iron end-members (instead of enstatite or ferrosilite, as the case may be). Names of phases that are not sufficiently well characterized to be considered accepted minerals in the eyes of the IMA are used here in quotation marks (e.g., “iddingsite”, “bowlingite”, “chlorophaeite”).

The author asks the readers for indulgence regarding the poorer quality of some photomicrographs. These correspond to old pictures taken from either borrowed or, more recently, broken or lost thin sections. In spite of their lower quality, some of them were retained to demonstrate or spectacularly illustrate a particular textural or mineralogical feature not observed in more recent or in other available thin sections. The more than six hundred photographs reproduced in this volume were carefully selected from more than ten thousand photomicrographs in the author’s collection.
Acknowledgements

The author thanks also all technical people of his Laboratoire de Pétrographie et Minéralogie des Altérations of ORSTOM, in Adiopodoumé, Côte d’Ivoire: MM. Lagou Kouadio Marcel (X-ray diffraction), Deme Hamade and Wayou Norbert (preparation of samples), Coubibaly Sissouro and Koffi Dakoa (preparation of thin sections), who have, during many years, helped the author to acquire accurate analyses and perfect thin sections.

Particular gratitude is expressed to my friend Claude Hanriot, Technical Director of the Laboratoire de Pétrographie of ORSTOM in Côte d’Ivoire, who prepared and finished most of the two thousand thin sections of the author’s collection. His care, constant attention to all the technical problems, supervision of the men and material of the Laboratory, control of all the steps in the preparation of the thin sections, and painstaking work in the impregnation of the soft samples, along with the daily long periods of sawing of the rocks and indurated materials, of gluing and thinning of the slides, and finally, of controlling of the correct thickness of the final thin sections, have all allowed the author to have at his disposal wonderful thin sections of fresh or weathered rocks, of soft soils and of indurated materials. Without the careful work of C. Hanriot, the complete illustration of this Atlas would have not been possible.

The author thanks also all his colleagues who have given or lent samples or thin sections from their collections and whose contribution has greatly enhanced the slide collection of the author. Among them are:

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The author is indebted to Dr. Daniel Nahon, Director of the Département des Géosciences de l'Environnement, Université d'Aix-Marseille III, he is deeply grateful to him for having accepted him, for many years, in his laboratory and for having given to him all the facilities for writing and achieving this book. Without his help and hospitality, the production of this book would have been much less agreeable, much more difficult and much more time-consuming.

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Introduction

Micromorphology is not a science in and of itself, but rather a research tool, a method for studying undisturbed samples of soils and of weathered rocks with the help of microscopic or, eventually, submicroscopic techniques. The micromorphological approach allows one to compare the textures and the structures that successively modify each other along a profile and in a landscape, to characterize textural associations, to identify the mineralogical constituents (skeleton, plasma, nodules, etc.) and the associated pore-volumes, and to specify their mutual relationships, in space and, where possible, in time. With this technique, it is possible to identify processes responsible for the weathering of rocks and for the genesis of soil, and to characterize or explain some of their peculiarities.

In contrast to the other technical methods for analyzing soil and weathered rocks (chemical, physical and mineralogical analyses), which are performed on bulk, crushed and homogenized samples, a micromorphological analysis must be made on undisturbed (and even, in some cases, on oriented) samples of soil or weathered rock. Most of these samples are composed of loose, friable and brittle materials; it is then necessary to harden the samples by impregnation with a synthetic product before preparing the thin sections. Coloration techniques, based on the impregnation of a colored product, are in some cases used for quick identification of macroporosity and for quantification of pore space.

Micromorphology is concerned where the purpose of a study is to identify mineral constituents, to describe qualitatively their shapes, or to study their distribution and their mutual and spatial relationships, or to deduce the genetic affinities existing among them. Detailed quantitative study, typically involving point-counting of mineral grains, and measurements of sizes, volumes, distances and orientations of the miscellaneous constituents or units, is called micromorphometry. The sum of these microscope-based techniques is sometimes called pedography, where soils and samples of weathered rocks are concerned, by analogy with petrography, the term used when studying the unweathered rocks of magmatic, metamorphic or sedimentary origin that form the geological bedrock.

Micromorphology, which is a laboratory technique, cannot be isolated from field studies of the landscapes, of the profiles and of their horizons. It is an odd technique in that it allows one, under certain conditions and with certain restrictions, to resolve, at least partly, problems raised by pedological or geological studies of superficial mantles. It is thus a key, but not a latch-key, and definitely a complementary technique. It is used after field studies and after the bulk analyses (by X-ray diffraction, for example), but necessarily precedes electron-microprobe analyses, because micromorphological analysis allows one to determine the kind of detailed analyses required, and to select the points or areas that exhibit an interesting feature worthy of further study.

The appearance and development, in alterites* and soils, of pore space and of new textures formed under the influence of supergene processes, pedoplasmation and pedoturbation (modifications that are independent of features inherited from the fresh rocks), result in the need for a new, specific, complementary and indispensable terminology. This terminology originates from the work of scientists studying the micromorphology of soils. For more details on this terminology, the reader should refer to the classic work Fabric and Mineral Analysis of Soils (Brewer 1976), to the Glossary of Soil Micromorphy (Jongerius & Rutherford 1979), and to the Handbook for Soil Thin Section Description (Bullock et al. 1985). The terminology to be used in this study of the patterns of weathering in rocks and alterites will be derived partly from this specific pedological terminology, and partly from the terminology commonly used by geologists and petrographers to describe rock structures and textures and to identify their mineralogical constituents.

* All terms flagged by an asterisk are defined in a Glossary at the end of the book.
Keeping in mind the general aim of objectivity, the description and classification systems must be, as far as possible, independent of any interpretation, which is necessarily subjective. If such independent systems can be readily applied in descriptive sciences, such as classical petrography and mineralogy, this necessity is much more difficult to maintain here. In micromorphological studies of mineral and rock weathering, one must keep in mind that the original primary mineral and all the derived secondary products are genetically linked to each other. Inheritances are present everywhere, and they are always subjected to further changes: under these conditions, it seems difficult, even irrational, to disregard the genetic aspect of the spatio-temporal relationships that prevail among the observed features, whatever the scale (crystal, thin section, profile, landscape) at which these features are observed and whatever may be their mutual relationships.

Consequently, where well supported by detailed observations on a sufficient number of good thin sections, prepared from carefully sampled and regularly distributed materials, according to the profiles and to the landscapes, micromorphology and micromorphometry very often allow the researcher:

♦ to identify and to specify the processes of weathering involved and to ascertain the succession of secondary minerals that developed at the expense of the primary mineral;

♦ to identify the pedogenetic processes and to visualize all the transfers of elements and all the concentrations (eluviation, illuviation, nodulation or concretion), and to follow the development of certain peculiar features (porosity, pedoturbation, etc.);

♦ to provide concise data, of mineralogical or microtextural nature, about the parent rock from which the weathered horizons and soils formed, and from which a good unweathered sample is not always obtainable;

♦ to explain the history of a profile, a toposequence* and a landscape by adducing some data about relative chronologies, obtained by comparative study of chemical, physical, mineralogical and textural analyses performed on a series of profiles regularly distributed along the slope of a watershed;

♦ to specify the degree to which the superficial covers and soils are autochthonous or allochthonous, and to shed light upon the importance of their internal modifications;

♦ to estimate the extent of weathering and evolution of soils and their nutrient content as unweathered primary minerals (weatherable minerals, lithorelics);

♦ to eventually visualize the supergene enrichments or concentrations of residual or neofomed minerals containing economically important elements (Al, Ni, Cu, Cr, Ti, Au, etc.), to specify the mineralogical structures or morphological textures in which these elements are incorporated or concentrated, and to give important data about the genesis and the history of these mineral deposits, and

♦ to identify the processes of evolution and degradation of building materials subjected to physical stresses (road pavement and building stones), or to aggressive climatic environments, and to pollution phenomena (building materials and historical monuments), and to bring, in some cases, some solutions to the problems raised by their preservation and repair.

Ultimately, micromorphological observations allow the researcher:

1) to compare, in the rocks, in the alterites derived from them and in the soils superposed upon them,
   ♦ the general macrostructures and mesostructures,
   ♦ the microstructures that are specific to each level,
   ♦ the content and the evolution of the mineral paragenesis,
   ♦ the grain size and its evolution through the profile,
   ♦ the particular and characteristic associations of minerals,
   ♦ the pattern of organization of the porosity and of the pore system,
   ♦ the concentration or the migration of material and
   ♦ its eventual deposition in receptive pore-space.

and 2) to classify the observed features according to their origin:
   ♦ petrological origin: inherited characters from the parent rock,
   ♦ secondary origin: inherited features from the weathered rock,
   ♦ pedological origin: microtextures developed by pedogenesis.
This partial list of the possible applications of micromorphology of soils and weathered rocks shows that numerous sciences and practical domains can be advanced by the use of optical microscopy: agronomy and agricultural methods, geological, geochemical and pedological cartography, exploration for mineral resources, geography and geomorphology, paleohistory and paleoclimatology, ecology and environmental study, investigations of the resistance and durability of materials, and the preservation of building and monument stones.

Although the main aim of this book concerns the micromorphology of weathered minerals, it is necessary to describe also minerals that have been altered by hypogene processes. Many primary minerals, as they occur at the base of the weathering profile, are not truly primary minerals. Independently of the later pedogenetic processes, they have commonly first been subjected to hypogene processes that have partly or completely replaced them by secondary minerals, of hydrothermal or metamorphic origin, for example. These secondary minerals are considered, by pedologists and geologists who study surficial weathered covers and soils, to be the primary minerals of their weathering profiles. This complex concept will be taken into account in the development of the following chapters and in their illustrations. See, for example, the chapter concerning polygenetic alteromorphs.
Part 1

General Concepts
The photograph gives a nearly complete illustration of many features to be described and analyzed throughout the book. The main feature consists of an intermineral network of open pores (Part 1) that surrounds partly developed alteromorphs in which denticulate remnants of clinopyroxene and a secondary smectite-group mineral are clearly recognizable (Part 2). The easy circulation of percolating waters through the intermineral network is responsible for erosion and deposition of materials and, consequently, for the irregularities of its walls; it is also responsible for the incipient degradation of the smectite-group mineral and for the occurrence of an external rim of colored material by absolute and relative enrichments of iron oxyhydroxides (Part 3). For a more detailed explanation, see photomicrograph 056.
Weathering and Alterites

DEFINITIONS

The word weathering has two different but complementary meanings. On the one hand, it designates all processes involved in the transformation, the disappearance, the appearance or the persistence of mineral species, including all chemical reactions and all movements of elements or of materials involved in these reactions. On the other hand, where used as a modifier, it represents also the weathering profile and the weathered material itself, formed under the influence of a weathering process, and occurring between the unweathered rock that makes up the basement and the soil horizons.

The word weathering will be used solely to designate those supergene processes responsible for mineralogical transformations, whereas the word alterite will be used to designate the weathered mantle that is the result of these processes.

The word alteration, in its broader meaning, includes not only the supergene processes of weathering, but also the hypogene processes which, under late-magmatic, postmagmatic, hydrothermal or metamorphic conditions, are responsible for the possible early transformation of rocks and minerals before the processes of weathering begin.

The International Society of Soil Science (Delville 1975, Stoops et al. 1979), gives the following definition:

Weathering refers to the partial or complete transformation, isovolumetric or otherwise, of rocks, soils or loose sediments, accompanied by changes in their color, texture, hardness or shape. These changes occur by partial or complete disappearance of part or all of the original minerals, and their possible replacement by a secondary crystalline or amorphous, authigenic or partly allochthonous material. The physicochemical reactions responsible for weathering involve, on the one hand, percolating or underground waters, carbon dioxide, organic matter and various ions or colloids dissolved or transported by those waters and, on the other hand, the crystal structure of the transforming primary minerals and the ions released from them. These processes generally tend to an in situ accumulation of soft, porous and easily erodable material, which is the main source of transported sediments. Although weathering may occur at greater depth owing to important fracturing or high porosity of the rock, most commonly it occurs near the surface or at shallow depth, under conditions of temperature and pressure prevailing at the Earth's surface. There are thus important variations in the intensity of processes related to the type of climate or paleoclimate. The main factors controlling the intensity or rate of reactions are: temperature, amount of rainfall, efficiency of drainage, topographic location, and also the texture and mineralogical composition of the parent material.

According to this definition, the term weathering has a meaning that covers all the processes involved in the formation of weathered mantles, but it does not apply to the mantles that result from these processes.

Summary

Weathering is a supergene process by which primary minerals, of magmatic, metamorphic or sedimentary origin, rendered unstable in the upper part of the Earth's crust, are destroyed and replaced by more stable secondary minerals, generally associated with a newly developed porosity. The minerals formed under the supergene conditions prevailing in tropical regions are generally hydrated or hydroxylated silicates and oxides or hydroxides of the least mobile tri- or tetravalent elements: Al, Fe, Ti, Mn, etc. Hydrated or hydroxylated silicates and carbonates of divalent elements (Mg, Ca) also are formed under temperate or dry climates.
Silicates and oxyhydroxides are not the only minerals to be formed in alterites and related superficial horizons. Indeed, under particular geochemical environments, specific mineralogical composition of the parental material, and under local climatic or topographic conditions, various anions also may be involved in the reactions and form carbonates, sulfates, nitrates, phosphates and halides, which will crystallize either in the residual rocks or in the lower parts of the topography.

Under more arid conditions and over metallic veins and orebodies, the above non-silicate secondary minerals are very commonly formed; in fact, they can be very useful in prospecting and mineral exploration. They may form insoluble and characteristic mineral parageneses, which are maintained in the weathered mantles: metallasiferous deposits (of Cu, Cr, Pb, U, etc.) commonly are capped by such a residual mantle, rich in carbonates, sulfates and other non-silicate minerals.

**Weatherability**

The rate of the chemical weathering of minerals is related to the mean annual temperature and rainfall in the region considered. The importance of rainfall is related mainly to the quantities of water that come into contact with these minerals, to the rapidity of water renewal, and to the ionic content of these waters. It is also related to the kind of reactions occurring at the surface of the minerals. Weathering is more rapid at sites of excess free energy, such as crystal defects, twin planes, open cleavages and microfractures. The rate of weathering of a mineral under the mean conditions of the Earth's surface determines its weatherability.

Among the many factors that influence the weatherability of the primary minerals and that, in many cases, control the nature and the micromorphological textures of the residue and of the neoformed products of weathering, the most important are:

1. The chemical composition and the nature of the network of crystals: the nature of the chemical elements that compose these minerals, the crystallochemical properties of the structures that host these elements before the weathering processes begin, their solubility in water, and the ability of structural modules to be integrated within the neoformed minerals; the aluminum- and iron-rich silicates (e.g., staurolite, garnet, epidote, kyanite, and many other minerals of metamorphic origin) are generally much less weatherable than are the magnesium- and calcium-rich minerals that make up the common rock-forming silicates of magmatic origin;

2. The presence of crystalline and chemical discontinuities: the occurrence, number and distribution of defects or discontinuities, such as fissures, cracks, and cleavages, which cut the minerals and divide them; the occurrence of structural, chemical or mineralogical discontinuities such as twin planes, chemical zonations and inclusions.

**Order of Weatherability**

Crystalline and chemical discontinuities are determining factors and are specific to each mineral group. The least stable minerals are invariably the minerals of magmatic origin, which formed under the more extreme conditions of temperature and pressure. Forsterite-dominant olivine, which is among the first-formed minerals during the crystallization of the magmas, is among the most weatherable silicate minerals. whereas the minerals of the amphibole group, generally formed under conditions of lower temperature and pressure, are much more resistant to weathering processes. That decreasing order of weatherability, first established by Goldich (1938), corresponds to the succession of minerals in the magmatic reaction series of Bowen (1928). Bowen documented the importance of a discontinuous series during crystallization. on the one hand, involving the ferromagnesian silicate minerals olivine, orthopyroxene, clinopyroxene, amphibole and biotite, and, on the other hand, the continuous crystallization of a plagioclase feldspar, from anorthite (calcic) to albite (sodic), and finally the appearance of minerals formed last during magmatic crystallization, such as potassium-rich feldspar, muscovite and quartz. These last-formed minerals are also the minerals that, under near-surface conditions, are the last ones to be weathered.

The decreasing order of weatherability also reflects important differences in the structural framework of these minerals. A potassium-rich orthosilicate like olivine, which is built of isolated tetrahedra, is the first mineral to be weathered, whereas the single-chain silicates (pyroxenes) and double-chain silicates (amphiboles) are weathered later. A framework silicate like plagioclase will be more or less quickly weathered according to the proportion of Al-O and Si-O bonds in the framework. The compensation of charges resulting from these substitutions involves the introduction, in the available spaces, of the mono- and divalent cations Na\(^{+}\) and Ca\(^{2+}\). Crystals of the more calcium-rich calcic plagioclase are more easily weathered than are crystals of the less aluminum-rich sodic plagioclase.

The sheet silicates (e.g., biotite and phlogopite) exhibit a wider range of weatherability; these minerals may be
weathered at the same time as clinopyroxene. This anomaly seems to be due to the more important physical vulnerability of these extensively cleaved minerals and to the mechanical brittleness of most of their secondary products. Quartz, which is a framework silicate exclusively built of silicate tetrahedra, is among the most resistant minerals and, consequently, it has tendency to be concentrated, in a relative way, in most alterites and soils.

During the first stage of weathering, most primary minerals begin to weather simultaneously, but at very different rates, in such a way that, over the course of time and at a certain distance from the front of weathering, one or more mineral groups appear completely weathered, whereas other groups appear unweathered, at least at the scale of the optical microscope. This concept could account for chemical zonations in the composition of the secondary products.

Within the weathering products after olivine, for example, the essentially magnesium secondary phase saponite, which is observed in

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The rate of chemical weathering of minerals depends on their chemical composition, on the chemistry of the weathering solutions, and on the kinds of reactions taking place at mineral surfaces.

Weathering occurs more rapidly at sites of excess free energy, such as crystal defects, dislocations, twin boundaries, open cleavages and microfractures.
Olivine-bearing clinopyroxenite
Koua Bocca, Côte d'Ivoire
Sampled at outcrop
Intramineral features: intramineral cracks in olivine
Objective: x 4
PPL and XPL

An single crystal of olivine, colorless in PPL and second-order bright green in XPL, exhibits an irregular and sinuous outline. The grain is in contact with smaller grains of clinopyroxene, and shows an incomplete rim of pinkish orthopyroxene. In XPL, the rim of orthopyroxene, at the right edge of the photomicrograph, is purplish blue, whereas another part of it, at the bottom and left edges, is uniformly colored in shades of brown. The point of interest here is the presence in the olivine crystal of an extensive network of intramineral protoclastic fractures, which are decorated by magnetite dendrites. Most of these fractures are absent in the orthopyroxene rim, although this mineral may well have formed at the expense of the olivine by reaction with a basic magma. The fractures do not continue through the adjacent minerals; they are true intramineral fissures or cracks. These fractures are generally the pathways along which processes of hypogene or supergene alteration begin in the mineral. There results an irregular linear or banded patterns of alteration. The intramineral protoclastic fractures commonly are very useful in recognizing the parent mineral of the altermorphs as forsterite (olivine), thanks to their curved habit, their distribution and their coating of magnetite, all features that are generally maintained, even within polygenetic altermorphs. Here, the surrounding minerals are hornblende, clinopyroxene, and opaque oxide minerals. All are anhedral and finer grained than the olivine and orthopyroxene.
T his aggregate of three euhedral crystals of augite exhibits nearly all the internal features that can promote the preferential inception of the alteration processes that may later affect the minerals. Under PPL, the pyroxene crystals seem fractured and crossed by many intramineral cracks. The orientation of some cracks is strongly related to the nearly orthogonal cleavages of the mineral. This first system will give rise, once the crystal is partly weathered, to secondary minerals arranged according to a regular pattern of crossing bands. Under XPL, the clinopyroxene is seen to be simply twinned according to a plane parallel to the long axis of the crystal. Secondary products will possibly be concentrated along this plane, whose orientation bisects the orientations of the main intramineral cracks. The large crystal exhibits a clear concentric zonation, which corresponds to rhythmic variations in the chemical composition of the crystal. The chemical zonation of the mineral is expressed by an optical zonation, whose characteristic pattern is clearly observed in the part of the crystal that is nearly at extinction. Not all compositions of clinopyroxene are equally resistant to weathering. The most weatherable zones of each crystal will be the sites of inception of the weathering reactions.
This anhedral phenocryst of augite shows, in its core, inclusions of cryptocrystalline magmatic material, probably trapped as melt (later, glass that devitrified) during rapid growth. The marginal part of the crystal is sector-zoned, and each sector displays oscillatory zoning. Large inclusions observed in the marginal part of the phenocryst are anhedral microphenocrysts of pyroxene and olivine. Note the regular six-sided shape of the crystal, small embayments of basaltic groundmass along some of its edges, and a few irregular intramineral cracks. The basaltic groundmass contains small, colorless, lath-shaped crystals of plagioclase, irregular grains of pyroxene and olivine, and minute grains of an opaque oxide phase, presumably magnetite. All these minerals are embedded in a cryptocrystalline basaltic groundmass, which appears dark brown in plane-polarized light and black under crossed polars.
METAMORPHIC PYROXENITE
Koua Bocca, Côte d'Ivoire
Sampled at outcrop

Intramineral features: inclusions and twinning in hornblende

Objective: x 4
PPL and XPL

In the contact area with the surrounding younger granites, this pyroxene-rich rock has partly recrystallized and, under the new geochemical conditions, new minerals have formed. Most of the original volume of the orthopyroxene and clinopyroxene crystals has been replaced by newly formed hornblende, in which residues of the partially resorbed minerals are still distinguishable. All these minerals are embedded in a large, late-formed poikiloblast, which can be either quartz or a feldspar. The photographs show the imbricated texture of the rock, in which a crystal of green hornblende exhibits the typical multiple twinning, and residual inclusions of pinkish orthopyroxene (C3); the residual grains of diopside also contain many inclusions of hornblende or actinolite (E4), whereas the material enclosing all of these minerals is a large poikiloblast of microcline. Small irregular inclusions of microcline also are visible within the main crystal of hornblende. It is evident that all these imbricated contacts between minerals, each of different weatherability, will give rise to complicated patterns of weathering. The readily weatherable remnants of orthopyroxene, for example, will be quickly weathered where crossed by a transmineral fissure. If completely enclosed within the much less weatherable hornblende, the same remnants may survive for a long time before being weathered in the upper part of the alterite.
**MINERAL PATTERNS**

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**009**

**GABBRO**
Sonora, Mexico
Sampled by F. Paz Moreno

Intramineral features:
parallel twins in plagioclase

Objective: × 4
XPL

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**010**

**ANORTHOSITE**
Rio Grande do Sul, Brazil

Intramineral features:
complex grid twinning in plagioclase

Objective: × 6.3
XPL

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In the photomicrographs, the multiple twins observed in feldspar-group minerals. The first one illustrates the simple polysynthetic twinning commonly observed in plagioclase, here of labradorite composition, in which regular straight bands, in shades of white, grey and black in XPL, regularly alternate through the whole grain. In the case here illustrated, the twin planes are not exactly perpendicular to the plane of the thin section. For this reason, the boundaries of the alternating twin lamellae are not very sharp or clear. The stage of the microscope is in such a position that there is maximum contrast of extinction between the two distinct sets of polysynthetic twin lamellae.

The second photomicrograph illustrates the more complex grid twinning less commonly found in plagioclase. Groups of polysynthetic twins are reciprocally arranged in such a way as to appear nearly perpendicular to each other.

In E2 and D4, both groups are intimately combined. Such small areas with characteristic grids may well extend throughout the entire grains. Small inclusions of quartz are irregularly scattered in the feldspar grain.
LEUCITE-RICH PHONOLITE
Mt. Cimini, Viterbo, Italy
From the Krantz collection

Intramineral features:
concentric distribution of inclusions and complex twinning in leucite

Objective: x 4
PPL and XPL

Fragmented: euhedral crystal of leucite set in a microcrystalline silica-undersaturated flow of phonolitic lava. In PPL, the colorless crystal shows three concentric lines of very small inclusions of glass, which was entrapped in the crystal during the last phases of its growth. Note that these linear arrays of inclusions are rigorously parallel to the external faces of the polygonal (trapezohedral) crystal.

In XPL, the isotropic character of this supposedly isometric crystal is disturbed by the occurrence of many polysynthetic twins, diversely but regularly oriented through most of the crystal. This pattern of twinning, related to a phase transition during cooling, may be considered a characteristic feature of leucite crystals, although it is observed also in some crystals of garnet. Irregular intramineral fractures, in some places radially distributed, divide the crystal into many small fragments; these become, in this way, more easily and more rapidly weathered.
Crystal of garnet (likely almandine) intergrown with quartz and muscovite (curved crystals with blue interference colors in XPL), from which it stands out quite clearly by its high relief. The crystal shows a distinctive pattern of internal inclusions of quartz, distributed along curved lines that form well-developed spirals. This so-called "helicitic" pattern is characteristic of syntectonic porphyroblasts of garnet, and is due to rotation of the crystal during its growth, under the influence of tectonic stresses, with progressive incorporation of minerals of the surrounding groundmass. Garnet-group minerals are isometric; the crystals normally are isotropic and extinct in XPL, although in some instances they are birefringent, and may show zoning and twinning in a manner similar to that shown in the previous illustration of leucite. Many intramineral fractures and cracks are randomly distributed and unevenly oriented through the porphyroblast. Where these internal defects (inclusions and cracks) are numerous, weatherable crystals of garnet are reduced to small fragments whose outlines are enhanced by iron-rich (in the case of almandine) or manganese-rich (in the case of spessartine) linear and banded deposits, which give rise to irregular septo-alteromorphs (see later, 310 and 311).
The phenocryst of plagioclase exhibits a discontinuous pattern of compositional zoning, characterized by the development of a homogeneous core surrounded by a rim that exhibits rhythmic (oscillatory) zoning. The concentric distribution of the zones is clearly visible in the lower photomicrograph, in XPL. The variability in chemical composition of these concentric zones is responsible for this variation of extinction angle and interference colors upon rotation of the microscope stage. The homogeneous core of the plagioclase phenocryst, in contrast to its marginal parts, contains many minute inclusions of melt (now glass), clearly seen only in the upper photomicrograph, taken in PPL. The presence of these defects will promote the weathering of the core, especially once the glass devitrifies, whereas the oscillatory variations in chemical composition will promote a concentric distribution of the secondary products, at least at the beginning of the weathering process.
MINERAL PATTERNS

017, 018
CALC-ALKALINE GRANITE
Toumodi, Côte d'Ivoire
Sampled at outcrop

Intramineral features: inclusions of epidote in plagioclase

Objective: × 4
PPL and XPL

THE INCLUSIONS observed within a mineral grain are not in all cases also part of the surrounding matrix, as in the former examples; inclusions may also develop from the host mineral itself under the geochemical influence of a hydrothermal process, for example. The central part of this plagioclase crystal (andesine) has been partly converted to a random assemblage of epidote grains (reddish in XPL), locally associated with irregular patches of microcrystalline sericite (greyish in PPL) by a postmagmatic process. This partial transformation is due to the preferential replacement of the central part of the plagioclase crystal, which is slightly more calcic relative to its more sodic margin, according to the general reaction: Andesine + H₂O = Albite + Zoisite. Where influenced by later processes of weathering, the epidote inclusions, which generally are less weatherable than their host mineral, may resist for a long time before being weathered, especially if the conditions of weathering are not too drastic. Such inclusions of epidote may clearly be distinguished as unweathered grains within a kaolinite-rich alteromorph formed at the expense of feldspar. Under conditions of ferrallitic weathering, in contrast, both feldspar and zoisite are weathered together to gibbsite.
MACROCRYSTALLINE ROCK
interlayered in a basaltic lava flow
Ribeiron Preto, MG, Brazil
Sampled at outcrop
Intraminal features:
zoning in a crystal of plagioclase
Objective: × 6.3
XPL

AMPHIBOLE-RICH CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Sampled at outcrop
Zoning in crystals of hornblende
Objective: × 4
XPL

The upper photomicrograph shows concentric zoning developed in a phenocryst of plagioclase (labradorite) whose margin is much more sodic than its central part. This concentric distribution is clearly expressed by the different interference-colors exhibited by the two distinctive parts of the mineral. The central part is white, whereas the outer part is nearly at extinction. The difference in chemical composition is also expressed by the presence, in the central part, of isotropic material in which cryptocrystalline kaolinite developed. In contrast, the outer part seems unweathered. The distribution of the products of weathering is influenced firstly by the presence of twins (several distinct lamellae run across the long axis of the grain) and, secondly, by the poorly developed cleavage of the mineral, which determines the incipient formation of an acantho-septo-alteromorph.

The lower photomicrograph shows the presence of irregular zoning in two well-developed crystals of hornblende. The presence of zoning reflects firstly the resorption of clinopyroxene (small remnants are still observable in the central part of the grains) and secondly, reaction with, and adaptation to, the surrounding material, influenced by silica-rich solutions during growth of the hornblende crystals.
The upper photomicrograph shows a subhedral crystal of clinopyroxene surrounded by yellow vermiculite and green hornblende. Incipient weathering results in the opening of the two cleavages in several places in the crystal. Large open cracks run parallel to the main faces of the crystal, and two thin, nearly perpendicular sets of intersecting cleavages, characteristic of all members of the pyroxene group, are clearly distinguished over the entire crystal. The development of incipient weathering ensures the visualization of a third thin cleavage, which forms grey bands of various thickness on both sides of the large open cracks.

The lower photomicrograph shows a six-sided basal section of an actinolite prism with regular cleavages, which intersect at 56° and 124° to each other, as is characteristic of all the minerals of the amphibole group. When subjected to incipient alteration under conditions of ferrallitic weathering, the network of cleavages will provide the preferential pathway for the replacement of the amphibole crystal by secondary iron oxides and hydroxides. At the end of the weathering process, such a basal section of a subhedral crystal will appear, in thin section, as a typical septo-pseudomorph whose ferruginous septa are distributed in a regular obliquely crossing pattern that delimits regularly shaped empty pores.
of a euhedral crystal of clinopyroxene clearly shows the pattern of orthogonal cleavages that is typically developed. The cleavages are not very regular nor continuous throughout the section. The number of breaks and the interval between them depend on many external factors, such as tectonic forces, and possibly also stresses induced during the fabrication of the thin section. The crystal contains a large inclusion of phlogopite, which is probably responsible for the irregular fractures that are superimposed on the well-oriented cleavages of the host mineral. The high interference colors normally observed in a section of clinopyroxene do not appear in a basal section, which is cut nearly perpendicular to an optic axis of the mineral. The grain thus remains optically quasi-extinct at all positions upon rotation of the microscope stage, and the interference colors are very low (first-order grey).
Here is yet another euhedral crystal of clinopyroxene (augite), this one cut along a plane parallel to one of the two cleavages. Such sections of euhedral pyroxene do not exhibit the eight-sided shape of the basal sections (as in the previous photographs), but they usually are diamond-shaped, or they exhibit a roughly rectangular shape. During the early stage of its growth, the crystal engulfed many inclusions of matrix, originally as domains of basaltic liquid, which crystallized normally once trapped. The beginning of ferruginous weathering allows the cleavage in the plane of the section to be rendered visible by staining with a reddish brown material. Without this stain, the cleavage would not have been visible, being entirely within the thickness of the thin section. The ferruginous compound, which normally appears as thin linear deposits of deep-colored material in a basal section, appears here as relatively large, pale-colored areas, whose size and shape closely correspond to the opening of the relevant cleavage.
**Actinolite-Rich Amphibolite**

Southwestern Côte d'Ivoire

Depth: 1.5 m

Intraminal features: intersecting and parallel sets of cleavages and transverse fractures in actinolite

Objective: × 6.3

PPL and XPL

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The thin section, cut in an actinolite-rich amphibolite, shows that randomly oriented elongate prisms of actinolite have been cut along different crystallographic axes, which allows observation of their different patterns of cleavage, and also the development of transverse fractures. These features are emphasized by an incipient weathering to iron oxyhydroxides, which (i) coat the peripheral outlines of the crystal by a centripetal process originating from the interconnected intermineral fissures (C2), (ii) penetrates the crystal along transverse fractures, with formation of residual empty pores on both sides of a central deposit of oxides and hydroxides (DE4), and (iii) enhances the characteristic cleavages of the amphibole minerals: a set of parallel cleavages (C3) where the crystal is cut parallel to its Z axis, and oblique intersecting cleavages (D2) where cut perpendicular to that axis. Note that where a rock is microdivided to such an extent, it becomes friable, and easily crumbles into loose sand grains just like a granitic grit, well before the weathering of the rock has proceeded to completion.
A large crystal of hornblende illustrates the network of two intersecting cleavages. The angles at the intersections, 124° and 56°, are typical of all members of the amphibole group. The regularity of that network only appears if, as in this case, the plane of the cut is a basal section. In many places, the two cleavages have been opened by internal movements, possibly as a consequence of weathering of the surrounding rock. These newly formed intramineral channelways will be preferentially followed during the weathering process, once this resistant mineral begins to destabilize owing to geochemical disequilibrium in the upper part of the profile. Such an opening of the cleavages, related to a physical process of weathering, is commonly observed only within the less weatherable minerals, which can reach the near-surface horizons without having been chemically weathered. These open cleavages, if connected with the general pore-space of the weathered rock, can be also the sites of easy accumulation of materials of allochthonous origin. Where a mineral is fractured to such an extent, either along its own cleavages or along transmineral fractures, its weatherability is much enhanced, because each fragment acts as a small grain, around which weathering can proceed peripherally and centripetally. Nevertheless, in describing such an altermoph, it will be necessary to consider the whole crystal, not each of its fragments separately.
Hornblende-rich clinopyroxenite
Koua Bocca, Côte d'Ivoire
Depth: 2 m
Intramineral features: intersecting cleavages in hornblende
Objective: x 6.3
PPL and XPL

These two photographs show the fragmentation of a large unweathered crystal of hornblende according to the internal network of its obliquely intersecting cleavages. The open cleavages are the pathways for efficient translocation of illuviated material, which promotes the formation of coatings along the interconnected intramineral pores. Once dislocated and subjected to internal movements, such cleavage fragments are displaced relative to their neighbors, and the fragments lose their simultaneous extinction under crossed polars, as is clearly seen in the lower photograph. Note that the hornblende is not chemically weathered, but physical factors have promoted its fragmentation. The illuviation of material is of allochthonous origin. The strongly weathered grains (A1, D5) consist of clinopyroxene which, in the lower horizons, has weathered to a saponitic secondary product. Most of the round black dots that are unevenly distributed are small quantities of grinding material trapped under the cover glass.
**Differentiation of the Alterites**

Most soil profiles that are studied by pedologists generally do not exceed a few meters in depth and consist of only the visible upper part of deep and thick weathering profiles. Where developed under humid tropical conditions, the lower portion of such a deep profile is usually described in a cursory manner only. More detailed observations performed on deep profiles, in the field and in the laboratory, show that the deeper level is generally not homogeneous. In fact, it can be divided into several distinct horizons, which are distinguished from each other by important differences in their fabrics, their textures and their mineralogical composition.

**Alteroplasmation and pedoplasmation**

A first distinction can be established according to the proportions and distribution of the volumes of parent rock that have been subjected to alteroplasmation, that is to say, replacement by secondary products.

At the base of the profile, or near the weathering front, alteroplasmation generally follows a planar pattern (linear pattern if observed in the two dimensions of the thin section or of the cut of a profile). This pattern is related to the pathways of the weathering agent as it progresses along the fractures, joints, cracks, and all planes of weakness that divide the homogeneous parent rock into hard volumes of various sizes and shapes. The phase corresponding to the parent rock is discontinuous, and each unweathered volume is separated and isolated from its neighbor by a continuous volume of weathered material.

In some circumstances, but less commonly, the planar pattern can be preceded by a linear pattern (speckled pattern in two dimensions) that corresponds to the digitate penetration of weathering into the parent rock. The parent rock may remain continuous even where the shape of the fragments has become very irregular and cavernous.

In contrast to this first level, in which many boulders and blocks of unweathered rock can be preserved, another level develops higher in the profile, above the weathering front, in which the volume of alteroplasmation is continuous, and the primary remnants are restricted to small lithorelics and to isolated grains of slightly weatherable or unweatherable mineral grains.

Above this lower level, mainly developed by alteroplasmation (saprolite), another level progressively develops in which pedoplasmation is the predominant factor. Just as in the first-described level of alteroplasmation, the level of pedoplasmation develops at the expense of the subjacent level, successively following comparable patterns (speckled, linear, planar and continuous patterns). Alveolized or degraded isolated alteromorphs, large elongate patches, and vertical or oblique roof-pendants penetrate the lower level. Ultimately, the continuous upper level that results from the complete disruption of the rock fabrics as a result of homogenization of the pedoplasma contains isolated skeleton grains. These are the only evidence of the original parent material.

As far as completely weathered rocks are concerned, another distinction was proposed by Chatelin (1974), mainly on the basis of macroscopic field observations. The distinction is based on the persistence or the disappearance of the lithological textures and of the original petrographic fabrics of the parent material. This fundamental concept results in the distinction between *isalcerites* and *alloterites* (Fig. 1).

![Figure 1. Vertical distribution of the various levels and horizons in a typical lateritic profile.](image)
The concept of isalterite

The term isalterite (from Greek इσα, = equal or similar) is only used to designate the weathered levels in which original fabrics and spatial relationships among minerals are well preserved. The concept of the preservation of the original volumes is only partly involved in this definition.

During the initial weathering of rocks, even where all original minerals are weathered, primary fabrics are generally preserved. In some cases, the original volumes also are maintained. Each primary mineral simply is transformed into or replaced by a new secondary mineral, or replaced by pore space, which has maintained the external shape (iso-alteromorphs, see later) of the original minerals and the spatial relationships pre-existing in the parent rock.

In spite of the persistence of the residual petrographic frameworks, the preservation of the original volumes of the minerals is not always exactly achieved, even though the original fabrics seem to be perfectly maintained.

Some weathering processes result in the formation of secondary sheet silicates, such as the minerals of the beidellite, montmorillonite, nontronite and vermiculite groups, whose mechanical behavior is different from that of the neighboring primary minerals and of the other secondary plasmas. These secondary minerals may be subjected to successive swelling and shrinkage, owing to the variations in the state of hydration of the profile during alternating periods of humidity and dryness. Their occurrence can result in the swelling of the weathered rock. This is expressed by an actual increase (but commonly imperceptible at the scale of the microscope) of the volumes initially occupied by the primary minerals (moso- and kata-alteromorphs, see later). If, in the rock, such minerals are not very abundant, and consequently, if they are isolated from the others, the swelling forms and opens a radial network of transmineral or intermineral fractures that penetrate into or between the adjacent minerals. These radially distributed fissures and fractures may remain open and empty, or they may be filled up by volumes of the swelling clays, which extend out beyond the original limits of the parent-mineral grain (echino-alteromorphs, see later).

In general, the increases in volume are not perceptible in thin section, especially if they are isotropic (equal in the three dimensions). Consequently, the original shape of the primary mineral seems to be well preserved. Only with a comparison of numerous, concise and comparative measurements of grain sizes, in the parent rock and in the weathered rock, could one confirm and quantify these modifications in volume. Such accurate measurements and comparisons are performed only with difficulty.

Modifications of apparent volumes

The necessary morphometric measurements are made, for each mineral grain, according to its largest apparent diameter and according to only one of the three orthogonal directions. A comparison of the lengths between the corners of two cubes, where the volume of the second one is double of that of the first one, shows an increase equal to the cube root of 2 (= 1.26), which corresponds to an increase of 25%. That increase in length could be imperceptible in thin section. Moreover, this example pertains to a mineral that has doubled its volume during weathering, which corresponds to a volume increase of 100%, a value far in excess of the increases normally associated with such transformations. This argument shows that an increase of volume of 20%, which is undoubtedly more common in weathered minerals, will not be identified, or even suspected, in thin section. Moreover, the observer cannot be sure that the grain size of the minerals, prior to weathering, is always identical throughout the whole rock, and over the whole thickness of the alteredites derived from it. It must be remembered that in a thin section, few minerals are cut through their equatorial section, and that few grains can, thus, give exact grain-size measurements.

If the volume increase results from an expansion in only one direction (weathering of micas to vermiculite or to kaolinite, for example, with an expansion perpendicular to the plane of cleavage of the nica), that increase will be easily seen under the microscope because the mineral has acquired an unusual aspect owing to the important modification of its shape. The unequal modification of the size of mineral grains is responsible not only for important modifications of their shapes (a square may become a rectangle, and a circle, an ellipse), but also for the partial dislocation or fracturing of adjacent or included minerals, with development of networks of intramineral and inter-mineral fissures.

Many minerals are particularly sensitive to such constraints. Hard but breakable minerals, such as quartz or magnetite, may be fractured or disjointed. Cleaved minerals, such as pyroxenes and amphiboles, can crumble into small polyhedral fragments. Minerals that are fragile owing to the habit of the crystals, such as long prisms of apatite or needles of actinolite, are cut up in numerous slices and separated from their matrix.
On the other hand, the very porous secondary microstructures, which are supported by a minimum of residual material (koilo-alteromorphs and some sepi-alteromorphs), are susceptible to settling and crushing owing to the weight of the upper part of the profile. This is expressed by a perceptible decrease in the original volumes, although a quantitative assessment of such a decrease is made only with difficulty.

This is particularly true during the weathering of rocks that contain an important percentage of completely soluble minerals (e.g., calcite, gypsum, apatite), i.e., those that do not leave any residual resistant framework after their weathering (koilo-alteromorphs). The cohesion of the alterite is maintained for a short time by the resistant framework of the other surrounding unweathered components of the rock. Step by step, these last minerals also are weathered, the alterites settle, and finally, the residual cover only contains a disordered arrangement of the unweatherable minerals and the deformed secondary products, in which all traces of original shapes and volumes have disappeared.

Some very porous and alveolar alterites are formed by septa of gibbsite and iron oxyhydroxides (septo-alteromorphs, see later). These alterites are much more resistant, and they are maintained uncrushed to important thicknesses. These well-crystallized residual frameworks (crystalliplasmas) are geochemically very stable, and they tend to be hardened, over time, by allogenic accumulations of materials and by further recrystallization. The ferralitic weathering of pyroxene- and feldspar-rich rocks produces alterites (in some cases called "gingerbread") in which the original microstructures and volumes are perfectly maintained for a long period of time through great thicknesses of the weathering profile.

Isalterites can be maintained, in this way, to thicknesses of several meters. They are almost always located, in a weathered profile, in the contact area with the parent rock. Nevertheless, this logical superposition is not always observed. In addition to the processes that have led to the formation of old weathered horizons, now capping the profiles, further weathering processes may follow, and give rise to different mineral parageneses, less resistant or susceptible to further degradation with disappearance of the original textures. These more recent weathering horizons are now intercalated between the unweathered rock, at the base of the profile, and the early-formed isalterite at the top of the profile. For example, residual isalteritic bauxitic layers can be observed above another more or less thick and more recent layer, mainly composed of kaolinite, in which the original textures are completely destroyed. Isalteritic weathered ultramafic rocks are commonly observed above more recently formed alloteritic levels because drainage conditions have been modified during the deepening of the profile. Smectite-rich argilliplasmas of the holo-alteromorphs after pyroxenes or olivine, developed under the conditions of restricted drainage prevailing in the recently formed lower part of the profile, are much more easily deformed than the crystalliplasmas of the first-formed septo-alteromorphs.

The secondary minerals, mainly clays formed in the deep horizons of the alterite, are not necessarily stable in the upper part of the profile. They may be transformed to or replaced by more stable clays, oxides and hydroxides. These last transformations and replacements are generally accompanied by the disappearance of the textural and micromorphological features inherited from the primary minerals and rocks. The isalterite is progressively replaced by an alloterite.

**The concept of alloterite**

The use of the term alloterite (from Greek αλλος = different) is restricted to the weathered horizons in which the original microstructures, inherited from the parent material, are no longer perceptible to the unaided eye. The distinction between isalterites and alloterites is often very subtle because disappearance of the petrographic textures is often more apparent than actual. A typical alloterite, as described in the field, can be identified, with the help of the microscope, as a true isalterite; the changes of colors connected with redistribution or partial dissolution of some constituents (especially the iron oxyhydroxides), with the accumulation of allochthonous material (silica or calcite, for example), or with the infilling of the residual pore-space by allochthonous material (manganese oxides, for example), may conceal the isalteritic character of the material and lead to erroneous interpretations.

This may be the case for alterites derived from basic and ultramafic rocks that are weathered under conditions of restricted drainage. At the macroscopic scale, when such a profile is described in the field, all the secondary products after the ferromagnesian minerals are sheet silicates (argilliplasmas) that are not readily distinguished from each other. The original boundaries between the minerals are obscured (crypto-alteromorphs).
morphs, see later) or very disturbed by the differential behavior of these argilliplasmas under alternating conditions of humidity and dryness (kata-alteromorphs, see later). Moreover, this isostamorphic process may be responsible for the formation of an irregular network of fissures, which can be emphasized by allochthonous deposits of iron or manganese hydroxides. These colored deposits may appear more clearly than the primary textures that they cut. At the scale of the profile, such a level can be interpreted as an alloteite. Later detailed study, at the scale of the thin section, will confirm the isalteritic character of such alterites: a new secondary structure is simply superposed on the original, but still identifiable, microstructure.

True alloterites are in many cases clearly separated from the parental material by an isalteritic horizon. They correspond to facies in which a new structure is superposed upon or has destroyed the original petrographic structures. There is always a process of evolution of the isalterites by plasma degradation, internal recasting, preferential leaching, successive concentration, late recrystallization, miscellaneous neoformations, and development of new macroporosity due to biological processes. To sum up, they are the result of external processes that progressively modify and destroy the previously inherited textures preserved within the isalterites.

As a general rule, the original petrographic textures are relatively well preserved during the replacement of the primary minerals by secondary products (primary plasma or alteroplasma), but they show a tendency to be obscured and finally destroyed during further transformations of these secondary products into a subsequent generation of minerals (secondary plasma or pedoplasma). Consequently, once an isalterite is replaced by an alloteite, the primary textures are lost, and the identification of the parent material becomes more and more difficult as the alloteritic character of the horizon becomes better developed.

Old ferrallitic covers, which commonly have outlived several climatic or geomorphological fluctuations, very often comprise a thick layer of old alloterites that caps a more recent layer of isalterites. A systematic and detailed micromorphological study, made on a series of closely spaced samples taken from the whole profile, generally allows one (a) to observe, step by step, the evolution of these successive textural transformations, (b) to identify, in the last steps of their evolution, the nearly vanished traces of the original textures, and (c) to recognize some specific and characteristic features, kinds of signatures, pre-existing in the parent rock or having appeared during the early stages of its alteration.

The transformation from salterite to alloteite is generally very gradual, and it occurs via transitional horizons, variably thick and irregular. Islands of isalterite can be maintained isolated within well-differentiated alloteite, and alloteitic areas can develop at a lower level, within an apparently homogeneous isalteritic horizon. The juxtaposition, at a large scale, of isalteritic and alloteritic textures may, in some cases, develop over a thickness of several meters, and thick transitional horizons may occur.

Around each textural unit enclosed within other textural units are developed, at a smaller scale, intermediate textures whose detailed study often leads to very interesting observations. These intermediate textures surround each well-differentiated unit over an interval of variable thickness, depending upon the extent of the natural processes and also upon the orientation of the plane of the profile front in relation to the orientation of the transformation concerned. These remarks also apply to another transitional horizon, situated lower in the profile, which corresponds to the weathering front of the rock. Weathering can develop through a certain thickness before all weatherable minerals have completely disappeared.

An upper level of alterite that lies upon another weathered material of different petrographic origin cannot be considered as an alloteite relative to the lower level. In this case, the parent rocks are different, and the abrupt changes of microstructures observed in the profile are the result of changes in the nature of the parent rock. In the same way, hybrid profiles are developed along a geological or petrographic contact involving, for example, volcanic ash accumulated on a basaltic lava flow, gneiss or micaceous schist in contact with granites, subhorizontal diabasic or gabbroic sheets within an ultramafic intrusion, textural alternations in a sedimentary series, or mineralogical alternations in a metamorphic sequence.

The distinction between isalterites and alloterites, at the macroscopic scale of the profile, is subtle, and can give rise to erroneous interpreta-
The concept of isovolume

The distinction between isovolumetric and non-
isovolumetric alterites is significant and interesting
(Fig. 2). If transformations and replacements are made
at constant volume, the unit of volume can be used as
a basis, together with the apparent density and bulk
chemical composition, to calculate the geochemical
mass-balance. This calculation allows quantitative and
exact estimations of gains and losses of material
recorded in the different horizons of the profile in rela-
tion to the extent of their weathering and relative to
the parent-rock. The isovolume concept was introduced
and used for the first time in 1955 by G. Millot and M.
Bonifas in a study of the processes of lateritization and
bauxitization of some rocks of Guinea in Western
Africa.

If the results of chemical analyses, obtained from
samples of an unweathered rock and the prod-
ucts of its weathering, are directly compared, quanti-itative information is not obtained concern-
ing the true mechanisms involved during the
weathering. The comparison only involves weight
proportions in rocks and alterites that have very
different densities. In fact, unequal volumes of
material are being compared (Fig. 2).

The geochemical balances established according to
the isovolume method are calculated by combining the
results of the bulk chemical analyses with the results of
measurements of the apparent density of the analyzed
samples. This method requires special care when the
specimens are sampled in the field and when they are
later divided, in the laboratory, into three distinct but
necessarily identical fragments to be used as follows:
the first one for the preparation of the thin section, the
second one for the bulk chemical analysis, and the third
one for the measurement of apparent density.

The term alloclerite is not synonymous with
allochthonous alterite, but with alterite that has lost
some microstructural characteristics. It may be tempt-
ing to apply the isovolume concept to the alloclerites
whose autochthonous origin is obvious. It is not
because the original microstructures have disappeared
that weathering has developed without preservation of
the original volumes, and that further transformations
have brought such major modifications that any
attempt to calculate a mass balance could not be made.
By this method, extended to the allochthonous allo-
clerites, it is often possible to identify and to quantify
transfers of material (SiO₂, Al₂O₃, Fe₂O₃, CaO, etc.),
which are not necessarily expressed by spectacular
readjustments of the mineral contents, such as they
may appear in thin section or by X-ray diffraction.
Whatever may be the arguments, the application of
the isovolume concept to horizons that are not strictly
alteritic seems, in most cases, as valuable as chemical
mass-balances made assuming of constant aluminum,
constant titanium, constant zirconium or constant quartz, for example.

The isovolume concept can be applied and the geochemical mass-balances can be estimated only where several conditions are satisfied simultaneously. It is necessary that the isalteritic character of the material be confirmed in thin section, and that the parent rock has been sampled; the genetic link between the alterite and its parent rock must be demonstrated. The sampling must be carefully done: identity among the pieces of a sample that are to be used separately for chemical analysis, for measurement of the apparent density and for the preparation of the corresponding thin section must be carefully evaluated.

Relative and absolute accumulations

The concept of relative and absolute accumulations of materials, introduced by D’Hoore (1954), is very useful to describe the micro- and macro-morphological features of samples and horizons and to interpret the variations of their chemical or mineralogical contents.

The domains affected primarily by either processes of relative or absolute accumulation (Fig. 3) are differently distributed within profiles and along toposequences. At a large scale, processes of relative accumulation mainly operate in the upper parts, whereas processes of absolute accumulation generally operate in the lower parts of the toposequences. Nevertheless, detailed study of the profiles and of the toposequences shows that the distribution, at a smaller scale, can be much more complex and imbricated (see later).

Relative accumulation concerns all materials (chemical elements or minerals) that are concentrated in situ by concomitant losses of the other chemical or mineralogical constituents of the rock during its weathering. In general, the most easily concentrated elements are the least soluble ones (Al, Fe, Ti, etc.), that form the most stable secondary minerals, such as gibbsite, goethite and anatase, whereas the most concentrated minerals are the less weatherable ones (e.g., quartz, zircon, metamorphic minerals).

Absolute accumulation can involve practically all the chemical elements, but the moderately mobile elements (Si, Fe, Ca, Mg, Mn) are the most easily concentrated in the lower parts of a profile or of a landscape. There, they can crystallize as secondary minerals such as quartz, goethite, calcite, gypsum, or a smectite-group mineral. Absolute concentrations of detrital minerals (mainly unweatherable minerals, such as quartz, zircon and many other heavy minerals) are commonly recorded in the lowest parts of the toposequences.

The behavior of elements during weathering

Depending on the conditions to which silica is subjected, it may be either relatively concentrated in or exported from the weathered rock. Silica can be relatively concentrated either as primary residual quartz, or as resistant primary silicates (e.g., epidote, zircon, garnet, serpentine), or as in situ secondary minerals (smectitic clays and kaolinite). In the other cases, it is leached away. The behavior of magnesium largely depends upon the conditions of drainage at the site of weathering. Under conditions of restricted drainage, magnesium normally enters the neo-formed smectite-group minerals, but only on a temporary basis. When the conditions of drainage are modified and where leaching becomes important, the smectite-group minerals are degraded, and magnesium is leached away. Under ferrallitic conditions, magnesium is lost simultaneously with elements such as the alkalis and alkaline earths.

Relative accumulation takes place during the first stages of weathering, at which time an important fraction of the elements is leached; the relatively accumulated elements are generally concentrated in the isalteritic part of the profile, and become the main constituents of most alteromorphs. Relative accumulation is in many cases related to the isovolumetric transformation of minerals and rocks, but there are many exceptions to this rule.

Relative accumulation, by virtue of important losses of the other elements, leads to the formation of highly porous secondary structures, especially where the secondary minerals are oxides or hydroxides of Al and Fe, which generally form porous and mechanically resistant septo-alteromorphs. The resulting volumes are not different from the original volumes, and the weathering is considered isalteritic.
Relative accumulation can play a role not only in the lower part of the weathered zone of a profile, but also at higher levels, where the early-formed secondary products are degraded and transformed into secondary products of a second generation (metaalteromorphs, see later). These are more stable minerals under the new geochemical conditions prevailing in the upper part of the profile.

Absolute accumulation leads to increases in content of chemical elements or minerals by migration and deposition of material coming from other parts of the profiles or toposequences. This material appears as infillings, either within the porous structures of the alteromorphs, or in the open macropores due to cracks and fractures opened through the parent material. All this pore space provides suitable sites for absolute accumulations of allochthonous material.

The accumulation of material in an absolute manner is not necessarily expressed by an increase in volume of the receiving structures, because it results in the infilling of its inner pore-space. Consequently, this increase of material without increase of volume is expressed by a perceptible increase of its apparent density. Materials that are accumulated as a result of absolute accumulation are often distinctly visible and recognizable in thin section: they are infilling materials within early-formed pore-space, from which they are easily distinguished either by their mineralogical nature, or by their crystallinity, or by their colors, shapes, arrangements, orientations and various other characteristics. In the case of infilling of a porous alteromorph, or "pore.alteromorph, the resulting entity is a cumulo-alteromorph (see later).

The absolute accumulation of an element within an unstable secondary mineral may induce mineralogical or chemical modifications that may be imperceptible in thin section. For example, the transmineral transfer of aluminum from the weathering of adjacent primary minerals may result in the mineralogical modification of the smectitic secondary clays formed after olivine. This modification, from Al-poor saponite to Al-rich nontronite, generally unsuspected under the polarizing microscope, can be detected only with the help of ultramicroscopic methods of analysis. In this case, the microscale transfer of Al corresponds quite well to an absolute, but microscale.
process of accumulation. As such, it will modify neither the bulk chemical composition nor the bulk density of the observed sample.

At the scale of the sample, and moreover at the scale of the horizon, this process of accumulation does not enter into account because it corresponds to local transfer, over very short distances, of elements between neighboring minerals or alteromorphs. The predominant process remains one of relative accumulation, which prevailed during the weathering of the rock and of its mineral components.

On the other hand, some elements that are accumulated according to an absolute process may appear to result from true absolute accumulations if the accumulated chemical elements come from beyond the horizon or even from beyond the profile. Absolute accumulations of silica, introduced from the upper part of the landscape, may invade lower porous horizons consisting of gibbsite-bearing septo-alteromorphs that formed during an earlier step of relative accumulation. This influx may transform them into kaolinite-bearing meta-alteromorphs (see later).

In the upper part of a toposequence, a horizon of absolute accumulation generally lies upon an horizon of lower relative accumulation owing to downward microtransfers of minimally soluble elements (Fe, Al). This induces, in the long run, the formation of hard iron-rich or bauxitic crusts, whose residual pore-space is progressively infilled by newly recrystallized material, and whose apparent and true densities are consequently increased.

In contrast, in the lower parts of a toposequence, absolute accumulations of elements generally tend to follow the movements of water along the weathering front, to participate in the formation of the weathering products, and to rapidly infill the residual pore-space of their alteromorphs. In this case, the level of absolute accumulation is the base of the profile, even extending into the cracks penetrating the unweathered rock. The accumulated elements in the lower parts of the landscape are, for the most part, the elements that were exported from the upper parts of the landscape. Depending on the available anions, on their solubility, and on the dominant role played by one of the main constituents, absolute accumulations of silica, of carbonates and sulfates, and of oxyhydroxides of Mn may form.

In the middle part of the toposequence, the distribution of the relatively and absolutely accumulated materials is related to the solubility of the elements in water. The upper part of the profile may be characterized by slow, vertical, absolute accumulations of less soluble elements, whereas its lower part may be invaded by lateral transfers and absolute accumulations of more soluble elements.

The transfer of elements in solution, their gradual concentration, and their later redeposition in the lower part of a profile or of a toposequence, correspond to chemical accumulative transfers (or migrations) of elements. These chemical elements were leached (absolute removal) from the rocks undergoing weathering, and are transported and redeposited (absolute accumulation) within the pore space of the receiving material.

Depending on the distances over which these elements were transported, several scales of transfer can be distinguished:

- **nano-** (intra) transfers (intra: within the boundaries of the original crystal),
- **micro-** (trans) transfers (trans: through the boundaries of adjacent crystals), and
- **meta-**. **macro-** and **mega-** (inter) transfers (inter: along the intermineral network of fissures passing between minerals or alteromorphs); the prefix is added according to the scale or to the distances over which the transfer is observed (mineral, sample, profile or toposequence). It is not related to the quantities of material transferred.

**Note:** The term transfer, used in some cases, does not seem to be a very suitable term because it is already composed from the root trans (from the Latin trans, through, and from the Latin transitive verb ferre: to carry). The term could be used only for the transcrystalline transfers. The term migration, derived from an intransitive verb, seems to be more suitable.

Absolute accumulation is not only the result of migrations of chemical elements carried as solutions, but also the result of deposits of detrital material carried in suspension (particle or plasma transfers) by waters circulating in the macropores. These are generally deposits (*illuvial* cauas*, argillans*, *ferru-argillans*) of clay minerals, in some cases deposits of very fine particles of quartz or oxyhydroxides of iron (*skeletans*,

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**PART I: GENERAL CONCEPTS**
Ierrans*). These deposits are generally well oriented by gravity or by capillarity in the macropores. Consequently, they can easily be distinguished from the alteroplasma formed in situ and from the residual material.

The process of relative accumulation accompanies the weathering process and leads to an in situ concentration of insoluble elements or minerals by concomitant losses of the more soluble constituents. These losses of elements generally lead to the formation of an important network of residual pore-space.

The process of absolute accumulation is a later one that leads to allogenic concentrations of more soluble material or particles invading the lower parts of the landscapes, infilling the early-formed residual pore-space, and possibly involving neoformation of minerals. It leads to a decrease of the residual porosity.
CHAPTER 2
Sampling

IN THE PROFILE

The weathered horizons and soils, the succession of textures and volumes, to discriminate pre-existing inherited structures from newly developed ones, and to establish the geochemical mass-balances among its different parts, it is necessary to study the profile from base to top.

The first sample to be studied is the deepest one: it is the fresh, unweathered rock, which must necessarily be the parent material of the weathered profile. It is an indispensable and irreplaceable point of reference.

The different levels in the profile represent the different stages through which the rock has passed from the initial unweathered state to the ultimate one, in which all the inherited primary structures have disappeared. This evolution is slow. In studying a weathered profile, it must be kept in mind that the upper levels are much older than the lower levels, near the parent rock. Consequently, climatic and topographic changes may have occurred, and may have progressively modified the process of weathering during that long evolution. But it must also be kept in mind that the profiles, even the oldest ones, are in continuous evolution, and that recently acquired features may have been superposed upon the old ones, or may have modified or even replaced them.

The mineralogical evolution, which starts from the rock and is continued into the upper part of the alterite, is then observed in its real sequence over a time scale whose duration is only poorly and relatively specified. A static study, made at a given moment of the history of the profile, allows recognition of this evolution in the course of time if, in the profile, the different stages of alteration are superposed upon each other, each level representing a more evolved stage than the level immediately below. Nevertheless, it must be kept in mind that these levels are subject to dynamic and ever-evolving processes. Thus the very evolved horizons, which are located today in the upper parts of the profile, have probably shown, in the past, mineralogical and morphological characteristics comparable to those now observed in the lowest part of the profile.

This reasoning implies that all the evolutionary steps observed today are synchronous, and that one must go further and further back in time gradually as upper levels are considered, in order to infer the original evolution of the observed horizon. In other words, it is necessary to think and to work according to a fourth dimension.

The macroscopic study of a weathering profile does not allow precise definition of the boundaries between the various horizons that compose it, especially where these profiles are sampled within deep and dark pits. The profile is generally seen as an alternating superposition of well-differentiated horizons separated by transitional horizons that exhibit intermediate features. It is then very tempting to take samples only in the characteristic horizons, and to omit sampling the intermediate levels. Subsequent micromorphological study of these well-characterized samples would show, in this case, only the initial and final steps of these partial evolutions, and would give little information about the details of these evolutions.

Consequently, it is necessary to take samples from the transitional horizons, which are the most suitable ones to yield information about the mineralogical and microtextural transformations. In general, samples can be systematically taken at an interval of 20 or 25 cm, in order to avoid accidentally missing an interesting horizon. It will be always possible, during later examination in the laboratory, to disregard the samples that are too similar to the adjacent ones.
The samples are taken as undisturbed prismatic monoliths, of variable size, and they must be carefully extracted and manipulated. According to their hardness and to the compactness of the weathered rock, the samples are extracted by digging four tracks around the selected volume with a knife, a plane-edged hammer or a chisel. The sample, once extracted, is later wrapped in paper or cotton for protection, and is enclosed in a plastic bag to maintain its humidity. Finally, it is sealed with adhesive tape. The prismatic shape and the constant dimensions of the samples facilitate their ordered packing and transport. Sampling and transport are in some cases made easier using rectangular metallic boxes, from 5 to 10 cm deep, with one or two removable covers, that are progressively pushed forward into the horizon, penetrating along its four edges. This last method of sampling is practical and provides good protection of the samples during their transport. In contrast, the extraction of the samples out their boxes is often difficult if the boxes cannot be dismantled. The volume of the sample must be related to the heterogeneity of the material, to the number of thin sections to be made from it, and to the number of analyses or measurements (X-ray diffraction, chemical analyses and measurements of apparent density) to be made in order to apply the isovolumetric reference-frame.

If the weight of the samples is not a limiting factor, it is better to prepare large monoliths of weathered samples. In this manner, if the monolith is accidently broken during its transport, it is probable that pieces of sufficient volume will be available upon unpacking. Monoliths that are too small will probably be reduced into many useless pieces of insufficient size.

In some circumstances, it will be useful to orient the samples in the profile before their extraction. In most cases, it will be sufficient to mark the top of the sample, because the other directions are not very critical. In some special cases, such as in the proximity of veins, fractures, and other geological or petrographic features, it will be useful to note some orientations and distances related to these features. This can be accomplished with the help of photos or drawings clearly showing the nature, the directions of these features and the distances at which the successive samples were taken. The same precautions must be taken in sampling the concentric weathered shells that surround boulders of unweathered rocks: each shell should be numbered separately and, where possible, also oriented relative to the central boulder (above or below the boulder).

**In the toposequence**

The study of a profile, isolated from its geomorphological context, supplies very fragmentary information only. The distribution of the horizons, their thickness, their chemical and mineralogical compositions, and their micromorphological characteristics are modified not only in the time scale, within the profile, but also in the space scale, with occurrences of lateral modifications along the slopes of the landscapes. According to the local climatic, topographic and geological conditions, weathering and pedogenetic processes may exhibit important lateral variations which, moreover, may have been modified according to the age of the various topographic levels that are stacked along the toposequence.

A good interpretation of these processes and of their origin will only be possible after a detailed and comparative study of several complete and graduated profiles, regularly distributed along a slope which is, itself, selected according to its representativity in the whole landscape. In other words, the true weathering profile to be studied is not only a vertical profile, but it is mainly a subhorizontal one delimited by the superficial topography (pedological horizons) above and the weathering front (incipient weathering) below.

Consequently, the sampling must be systematic. In a section of the slope, the samples must be distributed according to a regular vertical grid, with a high density of sampling in the vertical direction. Each vertical line, which is representative of a profile, a pit or a bore-hole, must be located according to the local characteristics of the slope, the variations of the plant cover, the density of the drainage network, and the geological or petrographic variations. According to the length of the slope and to its particular characteristics, a mean toposequence is formed of a catena of five to fifteen profiles separated from each other by variable distances.

Because natural processes, such as transfer and accumulation, generally act by gravity and are directed down the slope, it is better to begin the micromorphological study of a toposequence by studying the topographically highest profile. One then proceeds to the lowest profile and, later, back up the slope for a new micromorphological study, reserved this time for an inventory of the stages of weathering and for an identification of their successive inheritances.
The detailed study of all these toposequentially arranged profiles provides excellent insight into the natural phenomena, whose nature, chronology, mutual influences and inheritances are better assessed in the space and time scales than in an extremely detailed study of an isolated profile. To be convinced of this, it is informative to read the works of Bocquier (1973) about Tchad, of Boulet (1974) about Burkina, French Guyana and Brazil, of Delvigne (1965) about Côte d'Ivoire, and of Nahon (1976) about Senegal and Mauritania.

IN THE LANDSCAPE

At the scale of the landscape, the observations can be more complicated. Indeed, it appears that two perpendicular toposequences, the first one along the main slope of the interfluvial crest, the second one along the shortest slope, are quite commonly very different. The first toposequence displays in space the mineralogical transformations and the textural modifications. In contrast, the second toposequence condenses them by overlapping and telescoping, with eventual suppression of horizons or profiles that are well developed in the main toposequence.

Consequently, the study of the alterites and of the soils of a well-specified and homogeneous area, from the climatic, geological, and anthropic points of view, must be made in the three dimensions of the landscapes. The soil scientist must carefully choose the most interesting, the most complete, the most characteristic and the most representative profiles and toposequences among all the profiles and toposequences explored in the area, to avoid having to deal with too large a number of samples for later studies in the laboratory.

Many soil scientists, geologists and petrographers study only a few samples, often completely isolated from their geomorphological or structural contexts, with the aim of quickly obtaining new observations and interesting data to be briefly described in short papers or posters. For this reason, observations and analyses are commonly only made at the nanoscale (e.g., electron-microprobe analysis, transmission and scanning electron microscopy). Consequently, the mesoscale (profile, hand specimen) and the microscale (optical microscopy on thin sections) are often completely neglected.

One of the aims of this book is to demonstrate that many observations can be made and many explanations can be obtained from the careful study of thin sections of soil and rock samples correctly distributed along the profiles and in the landscapes. The author will be happy if his book can stimulate more scientists to undertake studies using micromorphology, at the scales described below. Also, he hopes to succeed in encouraging students to discover the natural beauty of minerals and textures, often unsuspected in their samples and not always revealed at the other scales of investigation.

One must remember that micromorphology is only a research tool, as much in the study of weathering as in the study of soils. It does not necessarily provide solutions to all problems. However, significant contributions are possible if the results obtained by this method are carefully compared to the data obtained from the field and laboratory observations. It is fruitless to disregard the profile and landscape data and to base all interpretation on only the micromorphological data resulting from isolated thin sections prepared from samples taken, at random, during a walk on naturally exposed profiles or outcrops.

No result obtained in the laboratory can be correctly explained without bearing in mind the fundamental field-based observations. Whatever the sample, soil, alterite or rock, it will reveal its mystery only if it has been carefully sampled in its geological or pedological environment. All data, even the most sophisticated data, must be always subjected to geological arguments. This way of working illustrates the motto of the International Geological Congress: "Mente et mal/eo".
Chapter 3
The Systems of Pore-space

At the scale of the optical microscope, one can distinguish, in a rock undergoing weathering, several main types of media, characterized by their porosity and by the physical properties of the primary and secondary minerals that compose them. These properties, mainly the porosity, directly influence the circulation of water in these media, the possibilities of ionic mobility and, finally, the real nature of the mineral transformations and neoformations.

Normally, these different types of media appear successively and invariably in the same order. They are arranged according to a double gradation in both time and space scales. Consequently, they can be clearly superposed in the various levels of the alterite at the scale of the profile. In contrast, if the rate of weathering is particularly high, which leads to a certain telescoping of the systems on each other, they can seem mixed, or superposed at the scale of the thin section.

There are three main types of such systems: contact microsystems, plasma microsystems, and systems of fissures.

**Definition, Classification**

Water is the main agent of the weathering of rocks. Its behavior within the various systems will be explained below, and its influence on the different types of weathering will be specified.

Weathering phenomena were attributed for many years to free water, which percolates rapidly through the superficial levels and which carries, by an advective process, the elements dissolved in the upper part of the landscape, eventually depositing them, by crystallization, in its lower part. Water is considered to be responsible for the differential spatial distribution of the secondary products derived from weathering. The system of fissures is the main factor controlling this process of quick circulation of the ions. In the plasma, and especially in the contact systems, the processes are different because the amounts of available water are much smaller and because, consequently, the properties and the behavior of water are different (Meunier 1980, Pédro & Delmas 1980).

**Water**, in a porous material, is better retained where it occurs in small quantities. The smaller the quantities of water, the more strongly water tends to be retained in the smallest pores of the material. In this way, water mobility decreases quickly in proportion to the decreasing size of the pores. Within the smallest pores of the plasma system, for example, water becomes virtually immobile, and ionic transfers result only from slow diffusion-controlled phenomena.

In poorly advective media, the mineralogical replacements invariably occur in the vicinity of less soluble and less mobile constituents, which support the neoformations of secondary phases. In the case of water that moves freely through the systems of fissures, the thermodynamic activity of H₂O is equal to 1. Within the plasma systems, water is more or less bound; it moves with more difficulty, the activity of H₂O is still more or less equal to 1. In contrast, within the practically anhydrous environment of the contact systems, the activity of H₂O may decrease to such an extent that the H₂O molecule is rendered unstable, and tends to become dissociated into H⁺ and OH⁻ ions. Under these conditions, hydroxylated but not hydrated secondary minerals are formed. Their chemical composition is closely related to the composition of the original primary mineral from which they were generated.

Where water is more abundant and more rapidly moving in a given medium, dissolved elements are easily removed, and less soluble elements can be complexed and removed; only very insoluble elements will be retained within the medium.

Depending upon the quantity of water available, very different secondary products can be formed from the same primary minerals. If the available water is
and each group or elements is deposited associated within the primary minerals are dissociated. The leached elements (except for Na and K) can eventually form carbonates or sulfates deposited in the lower parts of the landscapes, whereas sodium and potassium will only be concentrated in endorheic watersheds subjected to arid climatic conditions. In this way, the elements originally associated within the primary minerals are dissociated, and each group of elements is deposited separately, as in a large-scale "chromatography" (Tardy 1970), in very different and distant places.

From an olivine-, pyroxene- and plagioclase-bearing basic rock, for example, residual boxworks of iron oxyhydroxide (Fe), mixed Fe-Al hydroxide and gibbsite (Al) are formed, respectively. These three secondary minerals form polycrystalline, homogeneous and porous areas (septal-alteromorphs) without occurrence of element exchanges between the adjacent weathering minerals. No gibbsite occurs within the alteration products after olivine, nor is goethite found within the alteration products after plagioclase. Silica, Ca and Mg are completely leached away, and they can eventually be fixed in the lower parts of the landscape, the first as a constituent of kaolinite, or of nontronite, and the elements Ca and Mg as carbonates or sulfates, for example.

If the available water is less abundant and if its rate of circulation is slower, the weathering process is less aggressive, and only a portion of the soluble elements is removed.

From the basic rock of the former example, saponitic (Mg + Si) or ferriferous (Fe + Si) secondary clays are formed at the expense of olivine, ferriferous beidellite (Fe + Al + Si) is formed from the pyroxenes, and montmorillonite (Al + Si) can be formed after plagioclase. It is undoubtedly within this poorly advective medium, in which diffusion dominates, that the more important ionic exchanges (chemical transmineral microtransfers) are observed between adjacent domains of secondary minerals. Small quantities of aluminum enter the composition of the nontronite formed at the expense of olivine, whereas the montmorillonitic clays formed at the expense of plagioclase commonly are colored by imported iron oxyhydroxides.

If water is sparse or dissociated, and if its circulation is of no consequence, the alteration occurs without removal of elements, and even the more soluble elements are not leached away. Only OH⁻ ions are brought into the system. Where favorable thermodynamic conditions are achieved, hydroxylated minerals are formed. Their chemical composition is closely related to the composition of the precursor primary minerals.

Following the same example, serpentine-group minerals (Mg + Si) or cummingtonite – anthophyllite (Mg + Fe + Si) are formed after olivine, actinolite - tremolite - hornblende (Ca + Mg + Al + Fe + Si) or talc (Mg + Si) is formed after pyroxenes, whereas mineral associations of zoisite (Ca + Al + Si) and sericite - paragonite (Na + K + Al + Si) are formed at the expense of plagioclase. The element exchanges from one mineral to another during these replacements are very limited, and are effective over very short distances only.

**CONTACT MICROSYSTEMS**

Contact microsystems can operate, to a limited extent, in the first stages of weathering, when the primary minerals are still joined and closely bound in the practically unweathered rock, such as can be observed, at great depth, at the base of weathering profiles or in quarries. In contrast, contact microsystems commonly operate to a greater extent in rocks subjected to hydrothermal processes. These systems of contact correspond to the surfaces of destabilization and to planes of discontinuity.

These planes of discontinuity may be external surfaces of the mineral grains, which are generally true surfaces, situated in the suture planes between adjacent minerals. These surfaces form a continuous network: only poikilitically enclosed minerals are wholly isolated, and their bounding surfaces are not connected with that network. They also may be internal surfaces, which are generally potential surfaces and which correspond to planes of weakness in the crystal structure. They are cleavage planes, twin planes, alignments of micro-inclusions, etc. Only a portion of these planes is connected with the continuous network of grain boundaries. Finally, they may be uneven surfaces, which are true or potential surfaces, and which correspond to open or closed, intra- or transmineral microcracks. They commonly exhibit a parallel or a crossed arrangement, and result from tectonic stresses and from late- or post-magmatic movements.

At deep-seated levels, the rocks are compact and unweathered. Theoretically, there is no network of open fissures along which circulation of fluids can operate. The primary minerals are closely joined, and
the suture planes are closed. The only possible easy contact between water molecules and the rock lies at the margins of the veins, joints and faults that cut the rocks on a large scale and over long distances. Within an idealized small volume of rock, the contact between water molecules and minerals is locally restricted to contacts with external or internal crystalline defects or discontinuities. In this environment, only the very slow process of diffusion operates.

Where the concentration of water is very low, conditions of instability of the water molecules are reached, and the molecules are dissociated: the OH\(^-\) ions are fixed and progressively transform the anhydrous primary minerals into hydroxylated secondary minerals. Only OH\(^-\) ions are added to the medium, in theory, and the crystallochemical composition of the secondary minerals is closely related to the original composition of the primary minerals from which they are generated.

**PLASMA MICROSYSTEMS**

Plasma microsystems operate later, once the more weatherable primary constituents begin to be replaced by phyllitic plasmas or hydroxide minerals. Primary and secondary plasmas are distinguished.

**Note:** The size of the secondary crystals (kaolinite, gibbsite, goethite, etc.) can commonly be much larger than the size (2 mm) usually accepted for the definition of the "plasma". In this case, the more suitable term *crystalplasma* is to be used. If the secondary particles are micro-sized (less than 2 mm), the term *argillplasma* is preferred.

**Primary plasmas**

A primary plasma, or *alterplasma* (*i.e.*, a plasma of the first generation) consists of secondary crystalline microparticles developed at the expense of and within a primary mineral whose size and volume generally are maintained. The domain formed in this manner is an *alteromorph* (see below for the best definition of this general term). During the first step of its formation, the primary plasma is formed either as a thin film that surrounds the primary mineral or as a thicker rim that surrounds a residual remnant of primary mineral, but always inside its original boundaries. Once the primary mineral is later completely weathered, it is generally replaced by an aggregate of secondary minerals associated with an interstitial pore-space whose sum occupies the total volume of the parent mineral. The entity resulting from this replacement exhibits an internal texture that has in some cases been called the *miniphano­"septic* texture (Bisdom 1967a). This internal texture and the relative proportions of solid and porous volumes will be the main keys for the classification of the alteromorphs (see Part 3).

The alterplasma is generally stable in the lower levels of the weathering profile, and it remains practically unmodified as long as subsequent modifications of the conditions of weathering do not occur. Such modifications may be due to the relative lowering of the profile by processes of superficial erosion, to the thickening of the profile by lowering of the weathering front, to climatic changes, and to internal modifications of the pattern of water circulation.

With increasing extent of weathering and increasing volume of the residual pore-space, the abundance of water is much greater, and its role, more important than in the contact system considered earlier. Water is stable even if, at the base of this level, the activity of H\(_2\)O can be less than 1. Secondary minerals vary according to the conditions prevailing in this medium, to the quantities of water available, to the extent of its saturation with respect to secondary minerals, and to the rate of its renewal. The neformations are composed either of 2:1 clay minerals whose crystallochemical composition can still be very close to that of the replaced primary mineral, or of 1:1 clay minerals whose composition is only a weak reflection of that of the primary mineral, or of crystalplasmas of oxyhydroxides of the least mobilizable chemical elements such as iron, aluminum and titanium. To this decrease in the complexity of the secondary minerals corresponds a decrease in the degree of chemical inheritance.

Within such environments, in which microporosity plays a dominant role, the water is tightly bound, its renewal is slow, and ionic transfers occur by diffusion processes. Such transfers operate in both directions: addition of water, and subtraction of the soluble elements, which do not enter into the secondary products.

The ions that are liberated from the primary minerals diffuse slowly and migrate only over short distances before being incorporated into the neoformed secondary minerals. The formation of aggregates of microcrystalline gibbsite at the expense of residual remnants of feldspar, completely isolated in the newly formed pore-space of the alteromorph, provides a
good example of these intramineral migrations over very short distances (intracrystalline nanotransfers).

Ions also can participate, after their migration, in the formation of secondary minerals in adjacent alteromorphs (intracrystalline microtransfers). The formation of aluminous smectite-group minerals in an alteromorph after olivine provides a good example of the transfer of aluminum, originating from the adjacent weathered pyroxenes or feldspars, into an alteromorph after a mineral that originally did not contain aluminum.

Finally, these elements can be trapped by the water that circulates in the system of fissures, and they can contribute, by advection, to distant neoformations (intracrystalline macro- or megartransfers). For example, calcite-rich crystalliplasmas form by processes of absolute accumulation in the lower parts of toposequences dissolution.

The combination of the rates of dissolution of the elements with their rates of leaching determines the nature and rate of the recombinations of the ions and, in this way, determines the nature and the composition of the secondary minerals. The alteroplasma (or primary plasma) is progressively developed, and it gradually replaces the primary minerals. This process is called alteroplasmation.

Alteroplasmation is a process that results in the formation of plasmas, either argilliplasmas or crystalliplasmas, formed in situ by weathering of primary minerals. The inherited textures are minphantosepic* textures. The matrix that is progressively formed is characterized by the juxtaposition of primary plasmas and provisional and ephemeral skeleton grains made of undisplaced, variably weatherable residues of primary minerals. Alteroplasmation is generally developed at a constant volume and without disturbance of the original textures, even where residual voids are abundant. These newly formed entities, or units, which appear at the expense of primary minerals, are alteromorphs.

Secondary plasmas

Secondary plasmas develop at the expense of the primary plasmas. They commonly correspond to pedoplasm, and are plasmas of the second generation.

In the upper part of the weathering profile, under the lowest horizon of the true pedological profile, the primary microstructural features, which were inherited from the parent material and which were until now relatively well preserved, are modified and tend to disappear. These abrupt or gradual modifications are produced, on the one hand, by the appearance and the development of an important and organized system of fissures and, on the other, by the structural reorganizations and the mineralogical transformations that are induced by this network of fissures. The sheet silicates of the alteroplasmas are progressively fractured, displaced, degraded, incorporated to the matrix, impregnated and colored by iron hydroxides. As their size decreases and they are mixed into the secondary plasma, these particles ultimately become unrecognizable as distinct crystalline units under the optical microscope: alteroplasmas are replaced by pedoplasmas.

The combined effects of internal movements recorded in this environment, involving displacements of material, mineralogical replacements, and concentration, compression and stress-related processes, result in the formation of a secondary plasma much more homogeneous mineralogically and microstructurally than was the primary alteroplasma. The chemical and structural inheritances are progressively and definitively lost. The distribution of the skeleton grains, until now consisting of unwithered and undisplaced residual grains, is modified. Large grains are fragmented, their fragments are disjointed, separated, and displaced, and the fine-sized skeletal grains thus formed are scattered, to be finally more homogeneously distributed in the newly formed secondary pedoplasma (matrix).

The secondary plasma is formed from the aggregation of microparticles of secondary minerals, as in the case of the primary plasma. However, the material consists of microparticles of clay minerals and, consequently, most of these plasmas are argilliplasmas. The secondary plasma is first developed locally, at the expense of the primary plasma, in the contact areas with the initial fissures. It is later gradually and widely developed under the influence of the processes of pedoplasmation and of pedoturbation.

Alteroplasmas that are rich in smectite-group minerals and in 2:1 clay minerals are evidently the first ones to be subjected to further mineralogical and microtextural modifications. These secondary minerals are mechanically unstable. As such, they are easily fragmented or deformed under the influence of alternating conditions of humidity and dryness, they are
easily cleaved and dispersed under the influence of external mechanical factors, and they are ultimately weathered to newly formed clay minerals, or to oxyhydroxides. These phases are more stable under the new conditions of improved drainage induced by the development of the network of fissures.

Kaolinite-rich plasmas are much less sensitive to these modifications. The microstructures in which the kaolinite is found can be deformed by stretching, fracturing or dispersion, but their mineralogical nature is generally not modified. In spite of its microdivision, kaolinite will be dissolved or replaced by gibbsite only where subjected to the most extreme supergene conditions.

Ferrallitic crystallplasmas, which are essentially composed of iron and aluminum hydroxides, are very resistant to subsequent modifications. These minerals form a residual framework whose parts can be fractured and mixed with various pedoplasmas, but their mineralogical constituents can remain unchanged, even in proximity of the soil surface. Within the horizons that are characterized by absolute accumulations of iron and aluminum in the profile, these porous boxworks can be filled up with a new generation of hydroxides \((\text{cumulus-}\text{alteromorphs})\), which strengthens their frameworks and makes them less and less vulnerable to the mechanical and chemical processes prevailing in the superficial horizons.

The large-sized particles of alteration plasma, initially preserved within the pedoplasma, can be assimilated to the skeleton, in the pedological sense of the term. If these residual structures are voluminous and well preserved, they are \(\text{litharetes or alteraretes} \) (weathered lithoretics), depending upon the extent of their weathering (see later, in Part 4).

The pedoplasma also includes all the transferred plasmas, which are deposited as cutans by physical migration into the horizons of absolute accumulation, and which can be later preserved as papules in the pedoturbated horizons. The pedoplasma first appears and develops in the alloteritic level of the profiles, and later becomes dominant in the soil horizons.

The conversion of the primary plasma system to the secondary plasma system is accompanied by mineralogical transformations, with degradation and simplification of the chemical composition \((\text{chemical inheritances})\) of the secondary constituents. The petrographic microstructures

### SYSTEMS OF FISSURES

#### The network of deep-seated fissures

This network of fissures has a geological or petrological origin. It forms a megasystem that can extend from the parental material at the base of the weathering profiles, or exposed in quarries and outcrops, to the upper part of the superficial horizons. This network is inherited directly from the geological structures. It consists of fractures, faults, planes of schistosity, bedding planes, and cooling fractures. Its occurrence is independent of the superficial processes of weathering and predates them. The network, or its traces, normally extends throughout the autochthonous part of the weathering profile, and may even reach the soil horizons if these are developed from a weakly pedoturbated material.

The network of this megasystem of fissures commonly is open, and thus allows easy circulation of superficial water through the weathered levels to great depths within the unweathered rocks. This system exhibits varied and generally characteristic networks: parallel, closely spaced and finely anastomosing networks in schistose and gneissic formations, an orthogonal or polyhedral, irregularly spaced network in granites and in most endogenic rocks, a regular, commonly vertical and closely spaced network in effusive magmatic rocks, and parallel, densely spaced and originally subhorizontal networks in sedimentary rocks.

The thickness of the weathered horizons is strongly influenced by the extent and density of this network of fissures and by its orientation and its organization. The thickest weathered mantles are generally developed on vertically layered rocks, such as strongly inclined schistose or gneissic formations. The orthogonal network, which commonly is developed in homogeneously structured rock, generally gives rise to spherical and concentric weathering, and the size of the first-formed boulders is related to the original intervals between the fractures. This case is observed on granitic and, in some cases, on ultramafic rocks.
This network is responsible for irregularities and indentations developed at the weathering front. It is also responsible for the formation of weathering microprofiles, which can develop along both sides of the deep vertical or oblique fractures or joints, and for their possible infillings by clays and allochthonous materials transported over long distances. The micromorphological study of these deeply buried microprofiles, which correspond to particular geochemical environments, can be made only with the help of numerous and regularly spaced samples carefully taken across these layered microhorizons or across the concentric shells that surround the residual boulders. The mineralogical composition of such materials, in which allochthonous materials can be intimately associated with autochthonous material, is in most cases very complex. Their relative distribution and their relative chronology necessitate a careful study of numerous thin sections made from particularly well-distributed and well-oriented samples.

**The supergene networks of fissures and pores**

These appear in the weathered rocks as a result of the multiplication and opening of fractures, fissures, channels and pores through which the waters can move easily. These networks are potentially dependent upon the original structure of the parent rock and are strongly influenced by the supergene processes of weathering. Two main types of networks can be distinguished according to their origin: the authigenic and the allochthonous systems. Features of the two are reviewed below.

The authigenic system of fissures and pores appears and develops within the weathering rock. It results from the fracturing or fissuring of the rock and constituent minerals (transmineral fissures), from the dislocation and separation of the component minerals (intramineral fissures and pores), and from the formation of residual pores located either within the poro-alteromorphs (intramineral pores) or partly developed between the newly formed secondary products and the residual fragments (inter-plasma – mineral pores). The formation and evolution of most of these voids are due to the direct influence of the weathering processes on the rock, without intervention of external independent processes such as those involving human or biological activities. For better definitions of these systems of pores and fissures, the reader should refer to the work of Bisdom (1967a). Note that this kind of system of fissures and pores is very widespread only in weathered rocks and is, in contrast, rarely observed in rocks that were altered under hypogene conditions. All the secondary minerals formed under hypogene conditions have a tendency to fill the whole volume of the available space and, consequently, most alteromorphs formed under these conditions are halo-alteromorphs.

Transmineral porosity is generated either by the opening of pre-existing closed fissures formed in the parent rock under the influence of tectonic constraints, or by recent fracturing of the weathering rock under the influences of physical, chemical and mineralogical processes. The fractures cut minerals without following their intermineral contact planes, and they are commonly several centimeters or decimeters long.

These networks consist of (a) parallel sets of linear fissures along directions of breakage, or of curved fissures around residual boulders, due to physical or chemical processes, (b) radial sets of fissures regularly distributed around alteromorphs whose smectitic clay content may promote compressive stresses due to swelling under alternating variations of humidity and dryness, and (c) irregular networks of interconnected fractures in weathered rocks, in which the formation of numerous meso-alteromorphs produces unidirectional deformation of the weathering rock and, consequently, induces the irregular fracturing of its unweathered constituents, as in mica-rich rocks for example.

Transmineral porosity corresponds to the opening of fissures and fractures that traverse the rock and cut the mineral without following the grain boundaries. These fissures and fractures are commonly pre-existing within the unweathered rock, and are caused by mechanical or tectonic forces. These networks generally consist of parallel or crossing sets of interconnected fractures, which can extend over long distances and, when opened, can easily be coated by deposits of allochthonous origin. The transmineral networks can be observed at the megascopic scale of the rock outcrop, at the macroscale of the weathered profile, at the mesoscale of the hand specimen, and at the microscale of the thin section.

The intramineral network of pores is developed under the influence of differential mechanical behaviors of the plasmas and the residual unweathered minerals. It is not directly inherited from the parent rock, but its distribution and density can be strongly controlled by the parent rock’s textural and structural patterns.
Coarse- and medium-grained rocks that exhibit equant textures, such as granoblastic and lepidoblastic textures, are the most favorable for a well-developed intermineral network of pores. In contrast, fine-grained rocks, and rocks that exhibit porphyritic, poikiloplastic, diabasic textures, and, generally, all rocks with serrated or notched grain-contacts, are not favored to form regular networks of intermineral pores. The intermineral fissures can be locally relieved by short transmineral fissures upon intersection with cleaved, or large-sized, or elongate minerals.

The two surfaces that limit the opening of an intermineral fissure or fracture are generally accordant surfaces: their opposite margins exhibit complementary shapes, which can be fitted by an imaginary movement of translation. Nevertheless, it must be kept in mind that the direction of the opening of the fracture is not necessarily parallel to the plane of the thin section and that, consequently, both accordant walls of the fracture may not always be observed together in the same area of the thin section.

Under particularly favorable conditions of regular, close-spaced and interconnected intermineral fissures, the network is nearly continuous, and can extend over long distances. However, it allows the easy circulation of water only along a part of its extent, because most separation fissures are discontinuous and form chains of alternating opened and closed elongate pores.

At the scale of the thin section from deep-seated weathered horizons, it is not always possible to easily distinguish the opened from the closed sections of an intermineral network of pores in relation to the circulation of water. In contrast, in the upper part of the alterite, which is subjected to processes of suspension, transfer and deposition of colored clayey material, the distinction is easier. Moreover, the nature, the shapes of the alterationomorphic plasmas are modified at the contact with open fissures accessible to the circulation of water. Effects of oxidation or dissolution processes, development of an aureole of diffusion of iron compounds, and the subtraction or displacement of particles, are commonly observed. The occurrence of these contrasted features assists in the identification of this open network of fissures.

If the transported material has not been filtered prior to its encounter with constrictions along the fissures during the upper part of its travel, colored argillans and deposits of miscellaneous particles can occur in the open sections of the network of fissures. In contrast, if the circulation of water is slow and if the elements migrate in dissolved form, crystallaria and other banded deposits can be observed along both the opened and apparently closed sections of the intermineral network of pores. Similar deposits of material can also be observed along the transmineral networks.

**Deposits of dissolved and detrital materials**

In general, deposits of dissolution origin and those of detrital origin can easily be distinguished by careful observation of thin sections. The crystallaria or material deposits that originate from transport as solutions show a tendency to nucleate and grow perpendicular to the walls of the pore system, whereas those that originate from transport of detrital material show a tendency to be layered or microstratified parallel to these walls. In the first case, the length of the crystals very commonly corresponds to the thickness of the deposit, without variation of grain size, whereas in the second case, the detrital deposits exhibit a microlaminated texture in which small variations in grain size are recorded.

The residual mineral grains that exhibit shapes and sizes similar to the shapes and sizes of the completely weathered alteromorphs are generally not fractured, because they are avoided by the network of pores outlined above. The grains are then surrounded, in the plane of the thin section, by a peripheral, rounded or polygonal pore that is connected at several places to the intermineral network. In contrast, acicular crystals, coarse phenocrysts, and porphyroblastic and poikiloblastic minerals are fractured, and the resulting fragments are separated by open transverse fractures. The occurrence of such connected fractures greatly increases the weatherability of the minerals that they cross, and of the isolated minerals that are enclosed within them as inclusions.

**Transverse fractures** are those that cut a lath-shaped or acicular or prismatic mineral either perpendicularly or slightly obliquely to its long axis. Transverse fractures may correspond either to transmineral fractures where they cross the mineral concerned, generally with a slight modification of their direction, or to intramineral fractures, not relieved by external transmineral fractures, where caused by physical torsion or bending and consequent fragmentation of the mineral. Single transverse fractures are generally observed in the first case, whereas parallel sets of
transverse fractures are more commonly observed in the second case.

Among the intermineral systems of fissures or pores, one can also include the very common and widespread "circumnodular" fissures and pores. These develop around hard nodules, skeletal grains or lithorelics where they are embedded in a soft enclosing matrix. This system is mainly due to the differential behavior of the adjacent volumes. The hard and incompressible volume of the nodule does not experience any variation due to swelling and shrinkage, whereas the soft and malleable matrix can easily respond to variations in volume generated by alternations in humidity and dryness.

A continuous curved circular or angular polygonal open fissure surrounds the hard rounded nodule or angular lithorelic and completely separates it from the surrounding matrix. Where connected with other networks of fissures, these circumnodular fissures and pores may be infilled by allochthonous materials. These systems of circumnodular pores commonly are responsible for the formation and thickening of secondary indurated cortices around the original nodules or alteromorphs (sec Part 4).

**Intemimeral porosity** corresponds to the opening of the intermineral grain-boundaries, under the influence of physical or chemical processes. Physical processes generally form regular networks of discordant fractures that delimit the original or weathered minerals over important areas, whereas chemical processes (weathering) give rise to discordant intermineral fractures. whose irregularities are mainly due to subtraction of weathered material by circulating waters. The intermineral network is generally interconnected over important distances, and allogenic deposits are commonly observed.

Expressed in terms of volume, **intemimeral porosity** is generally much more important than the porosity resulting from the two previous types of system. It is a residual porosity, which is exclusively due to processes of weathering. Intemimeral porosity generally does not exist in primary minerals and rocks.

Intemimeral porosity, at the scale of the optical observation, practically does not exist in most unweathered rocks. This porosity appears and develops rapidly as soon as weathering is initiated in the rock or in its mineral components. It appears first as an aureole of pores situated either along the periphery of the alteromorph, peripherally to the residues of primary minerals observed within the alteromorph (peri-nuclear or inter-plasma - mineral pores) or, more rarely, as enclosed pores within these residues. The porosity is thereafter widespread as residual alveolar pores, closely associated with the secondary alteroplasmas and crystalloplasmas. The shapes and the distribution of these pores are described in more detail in subsequent chapters concerning the "pore"-alteromorphs (i.e., pore-bearing or porous alteromorphs).

The **transverse fissures and pores** formed by the breakage of brittle minerals that are either easily cleavable (pyroxenes and amphiboles) or easily fragmented owing to their shape (acicular, fibrous or tabular minerals) can also be grouped with intermineral porosity, although their formation does not always depend exclusively on the superficial processes of weathering. Among these brittle minerals are apatite and aegirine prisms, actinolite and tremolite needles, and tabular crystals of feldspar in diabasic and basaltic rocks.

**Intemimeral pore-space** is irregularly shaped and is formed within the alteromorphs where the secondary products do not occupy all the available volume of the parent mineral. Within partly weathered primary minerals, this internal porosity very commonly occurs as an empty irregular pore that surrounds the residual remnant(s) and that separates it (or them) from the newly formed alteroplasma (inter-plasma - mineral pores).

This alteroplasma is permeable to elements transported in solution. However, this internal pore-space, within the recently formed alteromorphs, is generally not connected with the intermineral network. Consequently, it is not accessible to particles transported by processes of advection. Intemimeral pores may persist empty for a long time before being filled up by allogenic materials.

The volume of the inter-plasma - mineral pore depends upon the nature and composition of both primary and secondary minerals; it also depends on the degree of mineral alteration. During the first step of weathering, when the residual core is still voluminous, the open space that separates it from the secondary plasma is small and barely perceptible in thin section. But with increasing weathering, the pore volume can become progressively more significant.

The occurrence, shape and distribution of residual pores within the alteromorphs are strongly influenced by the physical and crystallochemical characteristics of...
both primary and secondary minerals. On the one hand, they are strongly related to the regular or irregular crystallographic discontinuities specific to each primary mineral, such as the cleavages and networks of fractures (septop-alteromorphs), and the distribution of internal zonations and micro-inclusions (alveoporo- and centroporo-alteromorphs). On the other hand, the nature of the secondary products also influences the shapes and distribution of the interstitial residual pores, such as the planar and parallel sets of thin pores observed in the phyllepato-alteromorphs, the irregular large pores observed in the glemeno-alteromorphs, and the reticulated and hierarchized pores observed in the retipore-alteromorphs (see Part 3 for illustrated definitions of these terms).

For intraminal pores to develop, it is necessary that the volume of the secondary products be less than the volume of the primary mineral from which they are generated. The pore volumes are generally proportional to the difference between the molar volumes of the primary and secondary minerals and, ultimately, proportional to the volume of the exported elements, i.e., those that do not enter the structure of the secondary minerals.

If some immobile elements (Al, Fe, Ti) are maintained within the alteromorph as constituents of secondary minerals, the value of the ratio of the molar volume of the primary minerals (Vp) and of the secondary minerals (Vs) determines either the formation of an interstitial empty pore between these two minerals or the formation of protective surface-layers at the contact with the remnant of primary mineral. This concept has recently been developed by Velbel (1993). Where the ratio of these volumes (Vs/Vp) is less than one, the primary mineral is easily weathered to a porous alteromorph. Where close to one, this ratio determines the formation of a protective layer characterized by slow diffusion of the chemical elements. Once wholly developed, the alteromorph is compact and poreless; it is a true holo-alteromorph. Where the ratio is greater than one, it determines a relative unweatherability of the primary mineral under the geochemical conditions prevailing in the alterite considered.

The development of poreless alteromorphs (holo-alteromorphs), or of alteromorphs in which the porosity is too small to be easily observed at the scale of the optical microscope, is relatively rare in weathered rocks and minerals. In contrast, such alteromorphs are very widespread in transformations resulting from hypogene processes: for example, the replacement of pyroxene by amphibole, of feldspar by epidote, of olivine by "iddingsite", and of nepheline by natroline, generally gives way to compact and poreless holo-alteromorphs.

This pore volume is, in contrast, inversely proportional to the volume of the imported elements or constituents necessary for the formation of these minerals, such as water molecules necessary for the formation of hydroxides and clay minerals. The richer in soluble elements is a primary mineral, the more porous will be its alteromorph. For the same primary mineral, the more drastic the weathering processes, the more easily and more extensively the chemical elements are removed, and the more porous are the resulting alteromorphs.

For example, the weathering of a crystal of olivine, under conditions of restricted drainage (very limited export of elements), gives rise to a sheet silicate alteromorph whose residual porosity is not perceptible at the scale of the microscope (holo-alteromorph, see later). However, under more extreme conditions of ferrallitic weathering (two of the three elements are mobilized), weathering gives rise to a very porous alteromorph (septo-alteromorph, see later) of goethite whose solid volume is small and proportional to the iron content of the original olivine.

Intraminal porosity results from the replacement of a primary mineral by an aggregate of secondary minerals whose total volume does not fill all the available volume delimited by the boundaries of the original mineral. Its importance strongly depends upon the nature of both primary and secondary minerals, and therefore, upon the weathering process. This, in turn, is related to the rate of leaching of the elements and, consequently, to the drainage conditions to which the observed minerals are subjected. An isalterite formed under conditions of restricted drainage comprises only alteromorphs whose perceptible intraminal porosity is very minor (holo-alteromorphs). A similar rock, subjected to conditions of ferrallitic weathering, gives rise to an isalterite of low apparent density, whose alteromorphs are very porous (alveoporo-alteromorphs and septo-alteromorphs).
The three main types of authigenic secondary pore-space are easily distinguished in thin section.

Transmineral pores, issued from transmineral fissures and fractures, cut the rock, or at least cut several adjacent minerals, without following the boundaries between the original crystals. This kind of porosity frequently originates in the breakage of the rock by mechanical forces, independent of the nature of the minerals traversed. Its occurrence largely precedes the first stages of weathering. Transmineral pores commonly are connected with the general network of pores and, consequently, they are commonly filled up by later allochthonous deposits.

Intermineral pores disaggregate the rock over a certain thickness along the original boundaries between the primary minerals. Such pores can be formed either by mechanical forces (in this case, accordant surfaces are commonly observed), or by physicochemical processes, which are responsible for less regular discordant surfaces. In both cases, they are in general connected to each other and coated by secondary products of allochthonous or autochthonous origin.

Intramineral pores belong to the most widespread system of pores in the weathered rocks. They are formed within the alteromorphs by weathering and removal of a part of the chemical constituents of the primary minerals. Being without connection to the other types of pore space, they are generally not coated by allochthonous materials. Their distribution, shape and orientation may be related to the crystalchemical structures of both primary and secondary minerals.

The authigenic system of fissures develops under the influence of pedoturbation, which promotes many textural and structural modifications in the upper part of the alterites and in soils. The distribution of such fissures is largely independent of the distribution of the authigenic networks, which were potentially pre-existing in the parent material and which really became opened in the lower horizons. However, their distribution may locally be superimposed upon these previously formed networks. The authigenic system of fissures is caused either by external factors, such as colluviation along the slopes, collapse and settling by gravity, the work of the soil and subsoil by human activity, animals and plant roots, or by the direct influence of circulating waters, charged with dissolved or eroded material, or under the influence of swelling and expansion within the secondary argillplasmas.

Networks of channels and pores created in this way may exhibit important vertical and lateral extent, and the circulation of water is relatively easy. Biological factors are mainly responsible for the formation of channels and galleries of important linear extent, whereas physical factors are mainly responsible for the opening and widening of planar pores along the early-formed intermineral and transmineral fractures.

The cross-section of biological pores is generally circular. They are irregular and sinuous, and consequently they appear in thin section as chains of isolated and elongated pores exhibiting an elliptical outline. Only channels cut perpendicularly by the plane of the thin section can appear isolated and circular. Their biological origin commonly is confirmed by the occurrence of root sections or animal excrements (coprolites).

Large planar voids form by late distortion of the alterite and are widened by removal of material, under the influence of physical factors. They exhibit, in thin section, linear extensions and irregular openings: their walls no longer are accordant surfaces. They are in general the result of the easy circulation of water in the early-formed networks of intermineral and transmineral fractures. The irregularities of their inner surfaces are determined either by the weathering of the early-formed weatherable alteroplasmas or by the internal erosion of microparticles. Their walls commonly are colored by iron oxyhydroxides (hypocoatings) formed either at the expense of the previously formed ferri­ferrous smectite-group minerals or by oxidation and fixation of dissolved iron-rich components. These walls generally are coated by argillaceous deposits (clay cutans).

The effects of porosity on weathered material

In the upper part of the alterites, at the level of the alloterite materials and soils, all these networks of fissures are well developed and form an interconnected and open network that facilitates the circulation of water. Their influence on the behavior of the
materials and on their mineralogical and microstructural transformations becomes progressively more important. The migration of the ions liberated from the residual minerals and from the still weatherable alteroplasmas formed in the deep-seated horizons of the profile proceeds by advection.

The more soluble ions (Na, K, Ca) can be displaced over long distances, at the scale of the landscape, before being newly concentrated and fixed in the lower parts of the landscapes or being transported away by superficial networks of drainage. The less soluble ions (Al, Fe, Ti) migrate only over very short distances, at the scale of the mineral or of the thin section, whereas moderately soluble ions (Si, Mn, P, Ni) and ions that may be integrated in the structure of other secondary products (Si, Mg, Fe and, possibly, K) have diverse destinies according to the conditions of dilution or concentration.

Chemical elements migrate not only as ions in solution, but also in suspension, as microparticles of minerals. The occurrence of goethite or gibbsite in pores and channels can be due not only to the precipitation of hydroxides from very diluted solutions, but also to in situ degradation of ferro-argillans previously deposited from suspensions of microparticles.

On the walls of the fractures, the first-formed secondary sheet silicates are weathered either to oxyhydroxides or to other sheet silicates whose composition is simpler. Walls of fractures, and, in general, all the allotriomorphic levels, are the preferred site of the hydroxides of the weakly soluble metallic ions and of kaolinite. The bulk chemical and mineralogical compositions are simplified and homogenized in these transitional allotriomorphic levels. These processes are widespread in the soil-forming horizons.

Alteromorphs that result from the complete weathering of primary minerals into assorted smectite-group minerals are degraded slowly, with dissolution of part of silica and magnesium, and liberation of iron. The portion of the silica not leached away is combined with the aluminum to form kaolinite, either in situ or in the network of pores. Iron is fixed as oxides and hydroxides, which pigment the degraded or neoformed clays. This progressive and centripetal degradation develops along the networks of intermineral and transmineral networks of pores. A network of brown-colored rims is developed around the green-colored smectite-rich alteromorphs. On one hand, the margin between the neighboring alteromorphs is obscured by diffusion of iron, which forms opaque deposits. On the other hand, the regularity of the accordan surfaces of the previous network of fissures is progressively destroyed: parts of the system are widened by dissolution or erosion of the walls, whereas other parts are obstructed by locally deposited illuviation cutans.

Incompletely developed alteromorphs, which still contain residual remnants of weatherable minerals, are subject to the same processes as the previous ones. Their plasma content is degraded slowly, but the remnants of primary minerals are now seriously out of equilibrium with the new geochemical conditions. Weathering processes are now completely different, and kaolinite or oxyhydroxides can be formed owing to the leaching of the other cations and of a part of the silica from the earlier-formed smectite-group minerals. As a result, polyphase alteromorphs or meta-alteromorphs (or both) are formed (see Part 3).

A very porous lacework of plasma is formed. It is rimmed by brown-colored deposits of iron hydroxides. These deposits are more or less concentrically distributed because they are fixed, on the one hand, on the walls of the open fissure and, on the other hand, on the surface of the central residual mineral or on the inner surface of the residual central pore. From the center to the outer part of the alteromorph, one finds the primary mineral core with its own rim of oxFe (=iron oxyhydroxides), a perinuclear void, an inner rim of oxFe fixed on the smectite clays, a smectite-mineral-rich concentric band, an outer rim of oxFe resulting from the degradation of the previous smectite-group mineral, and the open volume of the surrounding fissure.

Moderately weatherable minerals (hornblende, muscovite, orthoclase, microcline), and the coarsest crystals of the more weatherable minerals (pyroxene or plagioclase), where they survived as residual cores in the upper part of the profiles, are mainly dissolved, with the formation of residual boxworks of hydroxides, without passing through the intermediate stage of a smectite-group mineral. They can even, under conditions of extreme leaching, be completely dissolved, without forming anything but empty, or nearly empty, alteromorphs (koal-alteromorphs and centro-poro-alteromorph; see later).

Very resistant minerals (e.g., quartz, epidote, rutile, zircon, iron-rich opaque minerals), which were fractured during the earlier stages, are now dislocated, displaced and carried away as a consequence of the removal of the microsized particles that surrounded and cemented them. The isolated fragments produced from a given mineral grain lose their original orientation (i.e., they lose their simultaneous extinction
under XPL), and they are randomly scattered and distributed within the secondary plasmas, in which they are henceforth embedded as skeleton grains. With their disappearance, the ultimate traces of the original textures of the parent material disappear, and only the mineralogical composition of the skeleton grains can give an imperfect picture of its original petrographic association.

In the soil horizons, the influence of the networks of fissures becomes predominant. Important increases in the proportion of pores are observed: pores, fissures, channels, galleries, tubules and chambers of all sizes and shapes are observed. They are formed by partition and opening of the material, by dissolution of the remnants of weatherable minerals, by internal erosion of the colloidal particles, and by the influence of important factors of biological origin.

A new distribution of material is observed: consequently, most of the inherited structures disappear, and the material is homogenized. It is composed of a secondary plasma (M-plasma* or S-matrix*) that encloses the skeleton grains of unweatherable minerals (sand and silt) and of residual fragments of parent rock (lithorelics).

**Discussion**

Each mineral has a specific spectrum of potential patterns of evolution. Consequently, within the alterites whose parent rocks have been weathered according to diffusion-dependent processes, an important variability is observed in the mineralogical nature of the secondary products. On the other hand, where weathering proceeds according to processes of advection, the mineralogical composition of the secondary products is simpler and more uniform.

The more weatherable the primary minerals, the less drastic the conditions of their weathering need to be; they can be weathered even at the base of the profile under conditions of restricted drainage. Their incipient weathering can even occur within the practically unweathered hard rock below the base of the sampled profile. The many kinds of secondary minerals formed may be later weathered to other generations of different secondary minerals. In contrast, the less weatherable the primary minerals, the more drastic must be the conditions of their weathering; they are weathered only in the upper part of the profiles, the number of possible secondary minerals is very restricted, and these secondary products are less easily degraded.

Among the most weatherable primary minerals, the olivine-group minerals and, to a lesser extent, the pyroxenes, exhibit the largest range of possibilities in patterns of weathering involving diffusion and advection processes. These very vulnerable minerals are the first ones to be weathered, even under conditions of restricted drainage characterized by slow circulation of ion-rich waters. More resistant minerals, such as muscovite and K-feldspar, are completely weathered only in environments of thorough leaching and strong advection. The secondary products are few in number (mainly kaolinite and gibbsite).

Minerals exhibiting an intermediate degree of weatherability, such as those of the amphibole group, may exhibit very different patterns of behavior depending upon the geochemical processes to which they are subjected and the mineralogical composition of the rocks in which they occur. Relative to the other components of the parent rock, an amphibole-group mineral may behave either as a very weatherable or very resistant mineral (Fig. 4).

**Where does one encounter weathered grains of hornblende?**

For example, during the weathering of an ultramafic rock in which olivine and pyroxene-group minerals are the main constituents, the more resistant hornblende is weathered after these minerals. Under these conditions, it can persist intact except in the upper part of the weathered profile, where it is directly weathered to iron oxyhydroxides without passing through a "smectitic" stage. In contrast, in the weathered profiles developed on more felsic rocks, with important proportions of more resistant minerals such as quartz and K-rich feldspar, the relatively less resistant hornblende is weathered in the lowest levels of the profile, in which the conditions of restricted drainage lead to the formation of a smectite-group secondary mineral. Such smectite will be weathered to iron oxyhydroxides only in the upper part of the profile, near the soil surface. In the first case, iron hydroxides are developed from the direct weathering of the amphibole (ortho-alteromorph, see below), whereas in the second case, they are developed by the degradation of the first-formed smectite-group mineral (para-alteromorph, see below). The structural
FIGURE 4. WEATHERING OF HORNBLende IN ISALTERNIC PROFILES DEVELOPED ON ULTRAMAFIC AND GRANITIC ROCKS, RESPECTIVELY.

A. Ultramaflie rock containing olivine, clinopyroxene, and accessory hornblende

A1. Lower level of the profile, in which the weatherable olivine and pyroxenes are weathered to holo-alteromorphic smectite, whereas the less weatherable hornblende remains temporarily unweathered. Signs of the incipient weathering of the very unstable olivine appear at a lower level than the pyroxenes.

A2. Upper level of the profile, in which previously formed smectite is degraded into alveolar pores and internal rims of iron oxyhydroxides (meta-alveolar-alteromorphs). Grains of hornblende are weathered directly to porous septo-alteromorphs (boxworks) of iron oxyhydroxides. At this level of the profile, all minerals are weathered.

B. Granitic rock containing quartz, feldspar and accessory hornblende

B1. Lower level of the profile, in which only the hornblende is directly weathered to holo-alteromorphic smectite, whereas the less weatherable feldspars temporarily remain unweathered. Quartz remains unweathered over the entire isalternic part of the profile.

B2. Upper level of the profile, in which previously formed smectite-rich holo-alteromorphs after hornblende are degraded to meta-alveolar-alteromorphs (alveolar pores and rims of iron oxyhydroxides), whereas the two feldspars are progressively weathered to glomerosepto-alteromorphs of gibbsite. Quartz remains unweathered up to the top of the isalterite.

Note that the thickness of the isalternic part of the profile is determined, at its lower level, by the first weathering mineral (olivine in the ultramaflie rock, and hornblende in the granitic rock). Its upper limit is determined by the lower boundary of either the alteritic cover or of the superficial soil.
inherences are different, whereas the chemical inherences are rather similar in both cases. In other words, to observe the weathering of hornblende to a smectite-group mineral, it is necessary to study the lower part of profiles developed on granitic and related rocks. On the other hand, to observe ferruginous boxworks after hornblende, it is necessary to study the upper part of profiles developed on basic and ultrabasic rocks.

Similarly, the alteration of olivine to iron hydroxides will be observed with difficulty; in fact, this primary mineral is considered to be among the most alterable or weatherable minerals. Consequently, even if it has not been subjected to hypogene processes of alteration, it is highly likely that this mineral will be completely replaced by a smectite-group mineral, even at the base of the profile, before it has the opportunity, in the more superficial levels, of being weathered to iron oxyhydroxides.

The weathering of olivine to ferruginous compounds generally occurs in recent flows of basaltic rocks and in deposits of volcanic ash, in which the olivine is subjected to near-surface weathering under conditions of efficient drainage. The weathering of olivine to iron hydroxides can also be observed in endogenous rocks subjected to efficient near-surface erosion. Outcrops may contain unaltered crystals of olivine. Weathering to iron hydroxides sporadically occurs where olivine grains have been partly altered to serpentine-group minerals or to "liddingsite", for example, and where their residual remnants have been, in this way, protected from weathering to a smectite-group mineral in the deep-seated levels of alteration ("armored" residual minerals).

In contrast, the first step in the incipient weathering of a Mg-rich olivine to a smectite-group mineral is rarely observed because this primary mineral is the first component of a fresh rock to be weathered. These hard and compact rocks are reached or traversed only with difficulty at the base of manually sunk wells. As a result, no samples are available for the study of the incipient weathering of the olivine-group minerals to smectitic secondary products.

A material is ultimately obtained in which are operating sensu stricto pedological factors. These lead to the formation, in the upper part of the profile, of a differentiated level composed of a group of distinct superposed horizons, each with its own particular mineralogical, geochemical and microstructural components. These soil horizons are characterized by an organization, a texture and a composition that are quite different from the lowest levels, either by the relative concentrations of the skeleton grains (A horizons), by absolute accumulations of clay minerals (B horizons), by continuously renewed accumulations and degradation of organic matter or, ultimately, by the homogenization and destruction of the previous fabrics and construction of new structures through near-surface factors of biological or anthropogenic origin.

To undertake a micromorphological description, one must progressively abandon petrographic techniques and terminology, and employ different techniques of identification and description, with the help of a more specifically pedological terminology.
Part 2

Patterns of Weathering
The photomicrograph illustrates the partial weathering of plagioclase under conditions of ferrallitic weathering. The original crystals of plagioclase are broken by irregular transmineral fractures and transverse cracks, along which weathering has begun. Thick septa of gibbsite microcrystals are regularly developed along this network of fractures; thin, brown lineaments along their median plane mark the trace of the initial fractures. Gibbsite crystals are regularly distributed perpendicular to this median plane, forming typical septa, whereas cavernous remnants of plagioclase are isolated between them. In the beginning stage of weathering, no inter-plasma-mineral pores (or, where present, only very small ones) are developed between the primary and secondary minerals. Later, once weathering has progressed, irregular pores develop at the expense of the residues, whereas the later-formed crystals of gibbsite agglomerate. The resulting alteromorph is a complex glomer-o-septo-alteromorph. More explanations are given in the captions to photomicrographs 308 and 309.
Chapter 4

Micromorphological Descriptions

The study proposed here mainly concerns the description and classification of the patterns of weathering of individual minerals. They are treated as isolated single grains, whether they occur as associated components within the original rock undergoing weathering or as truly isolated grains within the superficial loose materials (alterites, soils, alluvium, colluvium or volcanic ash). When a thin section is observed under the microscope, each mineral grain is systematically examined. One can express, in this way, the extent of weathering attained by each mineral and by all the minerals that constitute the components of the weathering rock. The sum of these partial observations allows quantification of the extent of weathering reached by the individual mineral and by the rock as a whole.

The following main morphological and mineralogical features must be observed and described:

- The extent of weathering, which is expressed by estimating the modal percentages of the residual minerals and of their replacement phases, the percentage of voids necessarily being included in the latter figure.

- The organization and distribution of pathways along which weathering progresses through the primary minerals, and the influence of the crystallographic characteristics of each primary mineral on the development and distribution of secondary products.

- The shape and size of residual fragments, their internal fissuring and fragmentation, and the orientation of these fragments.

- The mineralogical nature of the residual grains and of the secondary products and, eventually, the variations recorded in the coloration, orientation and the grain/size of the secondary minerals.

- The organization and distribution of the secondary pores formed by the weathering processes relative to the secondary products and to the neighboring minerals.

- The possible occurrence of several generations of secondary minerals generated from the same primary mineral under the successive influences of several different factors (polygenetic alteromorphs, see Part 3) or the association of several distinct but synchronous mineral phases formed under the influence of only one process of alteration (polyphase alteromorphs, see Part 3).

- The eventual occurrence of secondary minerals formed by ionic transfer between neighboring minerals or of abnormal distributions of secondary products beyond the original boundaries of the grain of primary mineral.

- The sites in the thin section where variations in the chemical compositions of the primary minerals are presumed, or where continuous or discontinuous successions of secondary minerals are observed. These sites could be targets for more detailed studies by ultramicroscopic methods.

The degree of weathering, either of the separately observed different mineral species, or of the whole assemblage of minerals that compose the rock or its alterite, is expressed by a number, from 1 to 4 (Stoops et al. 1979): the higher the number, the greater the degree of the weathering. The number 0 is restricted to fresh or nearly fresh minerals and rocks, in which less than 2.5% of primary material is weathered. Depending on the aim of the study, only the modal percentages of the products of weathering need be recorded, or perhaps only the proportion of all secondary products, regardless of their hypogene or supergene origin, is required. Most pedologists and soil scientists consider secondary minerals formed by hypogene processes (e.g., epidote, natrolite, actinolite) as "primary" minerals, upon which supergene processes will operate, to form "true" (supergene) secondary minerals.

Classes 1, 2 and 3 are restricted to minerals and rocks in which the secondary products (residual porosity included) do not exceed 25, 75 and 97.5%, respectively, of the originally unweathered material. Class 4 is restricted to rocks and minerals that are (nearly)
completely weathered, and in which the volume proportion of the residual primary material does not exceed 2.5%. All these percentages are estimated according to the areas of primary and secondary minerals observed and measured in the plane of the thin section.

In the case of relict minerals isolated in near-surface materials and sediments, an estimate of the degree of weathering is relatively easy if the original outlines of these minerals are well preserved and remain identifiable. This is true in the case of minerals that have been weathered after their transport and whose secondary products and pores have remained intact. However, in most cases, secondary products have been removed during transport of the material, and the original sizes and shapes of the mineral grains are no longer identifiable. The remnants are embedded within and directly in contact with their new surrounding matrix, without relics of alteroplasma.

In the case of partly weathered primary minerals, which are of the same mineral species and which are the components of a partly weathered rock, estimating the percentages is more difficult. In the volume cut by the plane of the thin section, all grains of the same species have not necessarily reached the same degree of weathering, especially if the alterite is developed in successive cortices concentrically developed around a residual boulder, in which case the weathering is necessarily progressive and gradual. In this case, it is better to observe separately each concentric band, and to attribute to each a different class (number).

In the case of more homogeneously weathered rocks, in which all grains of the same species have reached a similar degree of weathering, one must keep in mind that the plane of the thin section does not necessarily cut all grains through their center. Cuts that correspond to more eccentric sections will appear much richer in secondary products than sections through the core, especially if these minerals are weathered in a peripheral or centripetal manner. The smaller the section of such a grain, the more weathered it appears. In the case of alteromorphs in which pores are clearly distinguished, the volume proportion of the voids must be added to the volume proportion of the secondary minerals in order to correctly estimate the degree of weathering reached by the mineral species concerned.

The case of rocks considered as a whole, in which not all the primary minerals are distinguished from one another, is much more difficult to resolve because all these mineral components may exhibit very different weatherabilities. Indeed, many rocks such as granites and gneisses contain important proportions of very slowly weatherable minerals, or of minerals that will be weathered only under exceptional conditions. For example, can a granite, with 30% quartz, be considered as completely weathered if only the 70% of its volume represented by the feldspars and accessory minerals are effectively weathered? Such a granitic rock, where normally weathered, will not exceed class 2 of the weathering scale; it will be necessary to attain conditions of basaltization for quartz to be completely weathered and dissolved. On the other hand, a completely disaggregated and loose granitic grit or grus can seem, in the field, as a wholly weathered granitic rock, whereas after consolidation by techniques of impregnation, the grit can appear in thin section as a practically unweathered rock, at least from a mineralogical point of view.

Some apparent incompatibilities may result in this way, when field observations and micromorphological data are compared. This is the case for partly weathered rocks whose primary constituents are distinctly textured and structured. If the weatherable minerals are few in number and randomly and uniformly distributed in the rock, and if they are isolated from each other, the hand specimen of the rock may appear, to the unaided eye, fairly fresh. This is the case for basaltic rocks, for example, in which only the olivine grains and volcanic glass are altered or weathered. Such rocks will maintain their hardness, color, density and other physical properties. In contrast, weatherable minerals, even in low proportions but distributed according to continuous patterns, can give to the sample an aspect of a strongly weathered rock, which will not be confirmed by microscopic study. This is the case with layered rocks, such as mica schists, in which the weathering of the parallel and close-spaced layers of biotite can be responsible for the complete disaggregation of the rock.

Whatever the system of classification adopted, it is better to take into account the interpretations derived from micromorphological observations, even if it then becomes necessary to complement these results with a detailed morphological description of the samples, as sampled in the field.

The best approach certainly consists in beginning the descriptions of weathering by observing the evolutionary state of the most weatherable minerals and in selecting among them the largest grains, the most typical grains and the grains that do not exhibit natural or artificial defects (e.g., holes, air bubbles, particles of abrasive). The grains that show the largest apparent diameter are the grains that were cut closest to their equatorial plane and whose visible proportions of relict mineral fragments, of secondary products and
of residual pores are the most representative of the actual proportions. A photomicrograph or a drawing is generally useful for efficient completion of the micromorphological description of a thin section. These largest grains of the partly weathered minerals also are the best ones for eventual further analyses using ultramicroscopic methods. Thereafter, the homogeneity in degree of weathering of the mineral species concerned is verified by observing whether there are gradients in weathering from one point to another in the thin section and by comparing the results with the results obtained from the next thin sections (above and below in the profile). An estimate of volume proportions determined by point-counting grains of the mineral species considered, combined with the characteristic number of the class of weathering (from 0 to +), are generally sufficient to characterize the degree of weathering of the rock and of its mineral components.

**A NEW PARAMETER**

A new parameter is here introduced in which the relative proportions of residual primary mineral (P), secondary minerals (S) and residual voids (V) are each assigned an integer from one to ten, such that the total equals ten. In other words, the volume fractions of each of these three textural constituents are in effect rounded to the nearest ten percent, and the resulting number divided by ten. In this way, the volumetric proportions of the three textural constituents of a partially weathered alteromorph can be quickly recorded and reported.

For example, a parameter 2/5/3 describes an incompletely developed alteromorph in which two parts of residual primary mineral, five parts of secondary products and three parts of residual voids occur together within the original outline of the primary mineral. A complete holo-alteromorph is characterized by the parameter 0/1/0. An empty kollo-alteromorph is characterized by the parameter 0/0/10. The different parts of a complete septo-alteromorph can be expressed by a parameter of 0/3/7, for example, if no primary residues are observed in the alteromorph essentially composed of three parts of septa and seven parts of residual voids. If a part of the pore volume is infilled by allochthonous deposits, they must be considered, in the parameter, as pore space and not as secondary minerals.

**SECONDARY POROSITY**

Chemical weathering generally proceeds along discontinuities, micro pores and fissures, which may pre-exist in the original rocks and minerals. The progress of weathering promotes, in turn, the formation of a secondary network of pores, ephemeral or permanent, which influences the rate of weathering.

The general description of the distribution, the shape and the size of the pores follows the terminology of Brewer (1964). This terminology, although conceived for the micromorphology of soils, can easily be applied to the micromorphological study of weathered rocks and alteration. Nevertheless, it seems difficult to completely avoid the genetic content of the descriptions and of the classification systems because the observed objects are generated from each other and are in permanent evolution.

According to the classification of Bisdom (1967a), three main patterns of distribution of pore space are distinguished: transmineral, intermineral and intramineral.

**Pore-space along transmineral fractures**

Transmineral pore-space corresponds to pores that occur along fissures, fractures and cracks that traverse the rock and the minerals without following the boundaries between the crystals. Such pore space may have been widened as a result of supergene physical or chemical processes. The pores generally occur along regular planes (linear strings of pores when observed in thin section), which cut the grains without appreciable change of direction.

This network is formed under the influence of tectonic forces (primary transmineral fissures and cracks). Before the rock begins to weather, these transmineral fractures are closed, and generally marked by parallel sets of thin lineations or discontinuities that run across the primary minerals without modification of their chemical composition, and without occurrence of identifiable open pores.

In many cases, these inherited networks of fissures are the pathways along which hydrothermal and other hypogean processes transformed the transected primary minerals into a first generation of secondary minerals of hypogean origin. In this case, the outline of the transmineral fissures and cracks may be emphasized by the development of veinlets of secondary minerals of variable or regular thickness, such as talc or actinolite in fractured pyroxenes, serpentine-group minerals in fractured olivine, or epidote in fractured plagioclase. The mineralogical constitution of the veinlets is commonly specifically related to the nature of the
fractured primary mineral. The veinlets are successively composed of different secondary minerals, depending on the nature of the transected primary mineral. In spite of this rule of thumb, the mineral content of the veinlets is in general more uniform and related to the kind of rock traversed, for example, veinlets of talc through pyroxene-rich rocks, or of a serpentine-group mineral in olivine-rich rocks, regardless of the nature of the primary mineral transected.

At the scale of study with an optical microscope, no pores are clearly distinguished if this kind of material is altered under hypogene conditions. Under the influence of weathering processes, the early-formed transmineral fractures may be opened; this opening allows weathering along the walls of the fractures, with formation of secondary minerals of supragene origin. But the main part of the open transmineral pore-space is observed only in partly or completely weathered rocks. Observations are possible in the parent rock, where transmineral fissures typically are closed. Weathering processes preferentially follow these textural discontinuities. On both sides of the transmineral fissures, the minerals are weathered, part of the secondary products can be removed slowly, and an open system of fissures progressively develops in which the porosity can become optically perceptible.

Another kind of transmineral pore-space, of secondary origin, may develop as, for example, curved concentric networks of pores around residual boulders, fractures generated by internal stresses due to hydration and swelling of some smectite-rich alteromorphs, and fractures and pores developed under the influence of mass movements within the alterites and soils. To these types of transmineral pore-space of chemical or physical origin, pore-space of biological origin can be added in the upper alteration.

The primary networks of pores, mainly joints and large fractures, may penetrate the rock over long distances, and their dimensions (length and width) are far beyond the scale of the thin section and of the sample. This kind of large-scale porosity was discussed in the previous section (Part I).

Smaller and straighter transmineral fissures, at the scale of the profile or of the sample, may be interconnected with other transmineral and intermineral fissures and cracks, or they may extend over unsuspected distances. This important open pore-space, although of lower order, may be also infilled with later allochthonous materials coming from the upper parts of the profile. Derived from several meters higher in the profile, or even more, the content of the deposits may strongly contrast with the host material. These deposits, formed by a process of absolute accumulation, originate from material transfers either in solution or as suspensions from the upper horizons. Perceptible enrichments of the host rocks in silica, aluminum, iron, and manganese may result before appreciable weathering, regardless of the nature of the transected and infilled material. Deposits of green nontronite or of red kaolinite are commonly observed in the fractures running across ultramafic rocks. Halloysite and secondary apatite are observed as infilling material in practically unweathered rocks (Bocquier et al. 1983). If the host rock is not weathered when infilled, absolute accumulations occur before relative accumulations.

The term "transmineral" can be applied to the transverse fractures that commonly are observed in needle-shaped or in thin tabular crystals, or to the fractures whose planar shape, when crossing an easily cleavable mineral, becomes irregular and sinuous. The term "transmineral" is also applied to fractures and pores that cut amorphous materials (which are not minerals by definition) or poorly crystalline materials (devitrified volcanic glass). It can be extended to fractures and associated pores that cross microcrystalline rocks (e.g., basalts, schists) too finely for the observer to be able to follow, in a detailed way, the exact course of these fractures.

**Pore-space along intermineral fractures**

Intermineral pores correspond to the pore space that crosses the rock by going around and between the mineral grains, without crossing through them. If the intermineral pores are closely spaced and if they surround most of the component minerals, the rock loses its cohesion, and is rendered friable, as is the case, for example, in the granitic grits or grus.

The intermineral network can result from a physical process of alteration but, in most cases, it results from the disaggregation of the rock by processes of chemical weathering that promote the pellicular dissolution of all the weatherable minerals. The careful observation of the morphology of the pores commonly allows the identification of the origin of these two kinds of pore-space. Physical alteration produces open fissures and fractures that exhibit regular accordant walls. Chemical weathering produces irregular walls, generally not accordant, that are separated by openings.
of variable thickness; the isolated mineral grains, completely surrounded by their alteroplasmas, have an irregular, cavernous or denticulate shape.

In slightly weathered rocks, intermineral pore-space occurs as irregular, sinuous and randomly spaced alignments of alternately open and closed pores, depending upon the inclination with which the intermineral suture-plane is crossed by the fissure. This is the reason why the intermineral fissures and pores are rarely infilled by continuous allochthonous deposits, at least at the beginning of rock weathering.

In contrast, within the strongly weathered alterites, the intermineral network is more efficiently interconnected and opened, because it is formed and widened by peripheral dissolution and chemical weathering, and no longer only by mechanical fracturing. The circulation of water is facilitated along such networks, and cutanic deposits are much more widespread.

Coarse-grained or less weatherable primary minerals occur as isolated grains within more weathered alterites. These mineral relics constitute mechanically resistant units to the deforming forces generated within the more easily deformed alteroplasmas. Around these relics, a peripheral open fissure is developed. Linked with the general pore-space of the weathered rock by a network of radial fissures, these generally open peripheral pores can be filled by illuvial cutanic deposits.

Other types of pores may be grouped with the intermineral pores: these are the circumnodular peripheral pores, which preferentially surround either indurated fabric units, such as nodules or concretions, or elements of residual structures, such as lithorelics and alterorelics. These fissures and pores are preferentially developed around mechanically resistant units embedded within a much more malleable S-matrix. Theoretically, these pores form a closed envelope that surrounds the residual or concretionary unit. They appear, in thin section, as circular peripheral pores. Although these pores can be closed and isolated, they very commonly are linked with the general pore-space by a network of radiating fissures, which are perpendicular to them. These peripheral pores may be ephemeral; repeatedly and alternately, they are occluded or renewed according to alternations of the humidity and dryness within the surrounding matrix. Peripheral pores may also be artificially opened by drying the sample during the preparation of the thin section.

At the contact with open and interconnected intermineral pores, the primary minerals are partly weathered in a peripheral and centripetal pattern. The alteroplasmas so formed may undergo several modifications:

- Small particles of plasma may be dissociated, extracted, displaced, carried away, transported and redeposited at long distances. These internal processes of erosion and deposition contribute largely to the irregularity of the walls of the pores.
- Alteroplasmas rich in a smectite-group minerals may be degraded into minerals of a second generation (kaolinite or oxyhydroxides), which are more stable and more closely in equilibrium with the circulating waters. That later transformation is commonly accompanied by material losses, by residual deposits of iron compounds of relative accumulation, and by increases in porosity.
- The plasma, whatever their mineralogical nature, may be enriched by influx of iron or manganese oxyhydroxides, which diffuse and are deposited among the particles and so modify their coloration. These are commonly internal deposits, and hypocoatings* are consequently formed.
- Clay cutans and crystallaria may form locally. They progressively fill in the pores until the filling is complete, and thus stop the easy circulation of water.
- Clay cutans, which consist of particles removed from the upper horizons, may be distinct in mineralogical nature and coloration from the materials in which they are deposited.
- Networks of intermineral pore-space, which eventually can extend over long distances, may be preferentially exploited by microfauna and roots. Their walls are consequently enlarged and modified by processes of biopedoturbation. The pores may be partly infilled by materials of biological origin.
- Argillaceous particles of the S-matrix, in close contact with resistant fabric units, are commonly subject to mechanical constraints. They exhibit a strong concentric reorientation parallel to the walls of these units and form constraint cutans (granostriated b-fabric*).

**Intramineral pore-space**

Intramineral pores are localized within areas of alteroplasma, and are invariably found within the original boundaries of the primary minerals from which these alteroplasmas developed. Alteromorphs that exhibit observable internal pore-space are poro-alteromorphs (porous or

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PART 2: PATTERNS OF WEATHERING
pore-bearing alteromorphs). Intramineral pores generally occur without apparent connection with the intramineral pore-space that develops within adjacent weathered grains. Their relative distribution gives an important key for the later classification of alteromorphs.

More specifically linked with processes of alteration or weathering than intermineral porosity, intramineral porosity must be carefully observed. Its micromorphological description will be the object of more detailed studies in Part 3.

Intramineral pores result from chemical alteration of a mineral in which the volume of the products of weathering is smaller than the original volume of the primary mineral. The shape and distribution of these pores within the alteroplasmas provide important criteria in the description and classification of minerals undergoing weathering, and of completely weathered minerals. Where the size and shape of intramineral pores are uneven, and where they are randomly distributed, the resulting alteromorph is an alveoporo-alteromorph (see below).

Weathering generally progresses into the primary minerals in a non-uniform way. The development and distribution of the secondary products are strongly influenced by the distribution of specific textural features in the primary minerals. Among these, the more effective ones are planes of cleavage (pyroxenes, amphiboles and micas), twin planes (plagioclase and numerous other minerals), interfaces between intergrown products of a deuteric or metamorphic reaction (e.g., perthite, myrmekite, symplectite, etc.), inclusion-rich planes and planes that are the loci of crystallographic defects. The rate of weathering is also influenced by variations in the chemical composition of the primary mineral (zoned minerals).

The orientation of secondary particles may also be influenced by the crystallographic directions of the primary mineral as, for example, in the case of flakes of a smectite-group mineral in an alteroplasma after pyroxene or mica, and of ortho- or hydroxide microcrystals in a crystalloplasma after a feldspathic mineral. Irregular cracks, without any direct relationship to the crystallographic directions of the mineral, are also at least partly responsible for the uneven distribution of the secondary products and pores. Their irregular pattern is then combined with the regular pattern directly inherited from the primary mineral. This results in the development of a complex pattern of alteration.

The orientation and distribution of secondary products are influenced by these factors, as are the orientation and distribution of the pores that are associated with them, although both secondary products and associated pores are complementarily distributed. Within completely weathered grains of a pyroxene or garnet, for example, the iron oxyhydroxides form septa that mimic the networks of cleavages and fractures (septo-alteromorphs, see below), whereas the associated pores are distributed as isolated, closed and empty polyhedral volumes enclosed between these septa.

The shape and distribution of the pores within an alteromorph may also be influenced by the crystallographic orientation of the secondary mineral itself and not only by that of the primary mineral. This is the case for smectite-rich weathering products after pyroxene. These generally form well-oriented phyllopo-alteromorphs in which the pores are distributed parallel to the more or less opened cleavages of the secondary mineral, without being influenced by the cleavages of the primary mineral.

Most intramineral pores are isolated within the alteromorphs, without direct connection to the transplasma and intermineral pores. As a result, they are not reached by the free circulation of water, and they do not exhibit cutanic deposits of particles transported by such waters.

Intramineral porosity may also appear and develop at a late stage within the alteromorphs by degradation of the first-formed unstable alteroplasmas. The dissolution and leaching of several constituents lead to the formation of irregular alveolar pores (meta-alveoporo-alteromorphs), rimmed by new minerals formed from the insoluble part of the plasma (goethite or gibbsite). This new (meta-) pore-space may be randomly distributed, or it may be concentrically distributed according to the mineralogical or chemical variations of the degraded mineral constituents. Where residual pores are directly generated by weathering of the primary mineral, the resulting alteromorph is an ortho-alveoporo-alteromorph; where they are generated by the degradation of the first-formed secondary products, the resulting alteromorph is a para-alveoporo-alteromorph (see Part 3).

The inter-plasma-mineral pore-space that develops between the remnants of primary mineral and the peripheral rim of alteroplasma must also be considered as intramineral pore-space, although it is ephemeral, and will be replaced by a different kind of pore space after the complete weathering and disappearance of those remnants (alveoporo- and centroporo-alteromorphs).
Hornblende-bearing clinopyroxenite
Koua Bocca, Côte d’Ivoire Sampled at outcrop
Transmineral fissures through hornblende and clinopyroxene
Objective: × 4
PPL

Becoming partially transformed into hornblende by a postmagmatic process, the clinopyroxene of the original pyroxenite was intensely fractured. A set of parallel thin transmineral fissures runs across several adjacent crystals of clinopyroxene. These fissures may be many centimeters or decimeters long. During the partial replacement of the clinopyroxene crystals by large poikiloblasts of hornblende, the transmineral fissures have been maintained within the clinopyroxene, whereas they have been largely obliterated within the newly formed hornblende. In the hornblende, the original transmineral fissures appear as very thin and short relict fissures, whose distribution and orientation correspond to and are in continuity with those of the original intramineral fissures. The transmineral fissures, persisting within the clinopyroxene grains, have thus been replaced by many relict intramineral fissures in the replacement mineral. All have maintained the orientation of the original continuous transmineral fissures.
A pair of two subparallel transmineral fissures run across a typical sample of clinopyroxenite, which is mainly composed of inequigranular crystals of clinopyroxene associated with a few small crystals of orthopyroxene (E3.4-5); both pyroxene-group minerals may be locally enclosed within poikiloblastic brown hornblende (E4.5). The transmineral fissures have provided the channelway along which hydrothermal alteration has begun. The dark-colored bands are mainly composed of randomly oriented and distributed microcrystals of actinolite. The two thin light-colored lines that run along the central part of the bands correspond to the trace of the original fissures. These were widened, along their walls, by the hydrothermal process. A more detailed view of a similar transmineral fissure in a related sample can be seen in the next two photomicrographs (034, 035).
A large crystal of clinopyroxene has been cut by a transmineral fissure, along which part of the colorless original mineral has been transformed to greenish actinolite. The secondary amphibole is clearly visible in the widest part of the banded texture (D3), whereas along its thinnest parts, the fissure has given way to microcrystalline grains of actinolite without any particular orientation. The opaque grains of magnetite that are located along the pathway of the fissure remain undisturbed and unaltered, as can clearly be seen by comparing the original and secondary parts of the rock. Within the transformed bands, the pattern of distribution of the magnetic grains is very similar to the pattern within the original rock. In this type of clinopyroxenite, the magnetite and the other opaque minerals seem to be either intersertal or enclosed crystals.
In the upper parts of the landscape, in the contact area between ultramafic and granitic rocks, both rock types may be found interlayered in the same profile. Within the granitic layers, mixed smectitic and kaolinitic clays infill the open transmineral fractures in the minerals of the granitic rock. Most fractures are connected, and they surround polymineralic fragments of rock, which later will be released from their matrix to form isolated lithorelics. In these illustrations, a large grain of microcline has been fragmented into several irregular fragments by wide transmineral fractures, which have been infilled by homogeneous clayey material. Microlaminations or variations in grain size are not developed. These infillings are crossed by irregular empty cracks. Small fragments of the primary minerals are engulfed in the infilling material. Most of these fragments are relics of weathered and oxidized crystals of biotite (mainly visible in C3 and A4-5). The weathered biotite seems to be the main source of the clay material of the transmineral infillings. In this case, the infilling material has a sub-autochthonous origin, and does not come from a very distant source. The observation of the next photos (038, 039) will confirm this inference. Note that the separated fragments of microcline have not maintained the originally homogeneous orientation of the large microcline crystal. Three areas of myrmekite are shown in C2, C3 and E4, and quartz grains are visible in the upper part of the photomicrographs.
038, 039
INTERLAYERED ROCK
Koua Bocca, Côte d'Ivoire
Depth: 3 m
Transmineral fracture
Material displacement over short distances
Objective: x 4
PPL and XPL

The rock layers that exhibit an intermediate composition, clinopyroxene and hornblende, derived from an ultramafic rock, are more abundant and generally enclosed within large oikocrysts of feldspar. In this sample, the feldspathic component is not weathered, whereas the mafic minerals, mainly the clinopyroxene, are largely replaced by a saponitic clay mineral. The wide transmineral fracture that cuts the rock is infilled with a smectitic clay whose chemical composition is very similar to that of the type of smectite derived from the weathering of the clinopyroxene. Compared with the earlier photomicrographs (036, 037), taken from an adjacent sample, it is obvious that the mineralogical composition of the infillings depends strongly on the nature of the fragmented rock. Consequently, these infillings are subaustochthonous, and illustrate material displacement over short distances. Fragmented alteromorphs after clinopyroxene and fragments of unweathered hornblende and microcline are engulfed within the infilling material. These fragments have not been displaced, as is indicated by the relative position of the fragments of green hornblende (C4-5). The infillings seem to be formed gradually with the opening of the fracture, small mineral fragments being randomly released from the walls of the fracture and immediately trapped within the infilling material.

PART 2: PATTERNS OF WEATHERING
A large fracture has been opened in a relatively fresh rock composed of clinopyroxene, olivine, hornblende and opaque minerals. The distribution of the partially weathered grains of clinopyroxene (B-C1, E4) indicates that weathering started after the opening of the fracture. Only the pyroxene grains that are located along the walls of the fracture are partially weathered. The more weatherable crystals of olivine are completely weathered to greenish smectitic clay. A large alteromorph after olivine (D1-2) has been cut by the fracture. Part of it has remained enclosed in the original rock, whereas the other part has been engulfed in green smectitic clay of illuvial origin. These allochthonous materials are produced by the weathering of rock in the upper part of the profile. Microparticles are easily loosened from the alteromorphs formed at the expense of pyroxene-group minerals and olivine by swelling and shrinkage, and transported to greater depths along the large continuous fractures. These processes are continuously operating, even after formation of the illuvial material, which explains the microtextures of these deposits. The clay material itself is crossed by numerous irregular fractures, with more or less accordant surfaces. Slight degradation of the smectitic clay particles induces the formation of a thin brownish rim of iron oxyhydroxides around each of these fragments.
TRANSMINERAL FRACTURES

042
WEATHERED PYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 6.2 m
Transmineral fracture
Material displacement over long distances
Objective: \( \times 2.5 \)
PPL

043
WEATHERED PYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 6.2 m
Transmineral fracture
Material displacement over long distances
Objective: \( \times 4 \)
PPL

Ferrallitic alterites and soils, the allochthonous deposits of illuviated clays are mainly composed of particles of more or less iron-rich kaolinite, which may occasionally be associated with silty particles. These materials give way to microlaminated infillings, in which fine and coarse layers may either alternate regularly or form deposits whose grain size varies progressively within the thickness of the infilling. Disordered internal movements of the soil material along the slopes of the landscape promote the irregular faulting of the infilling, and the relative displacement of parts of it, as can be clearly seen in these two photomicrographs. Several grades of faulting are developed; coarse fragments, derived from macrofaulting with large relative displacements, also have been subjected to internal microfaults, which result in the slight relative displacement of their microlaminations. Many secondary cracks are randomly distributed in the illuviated material. Since they do not show any coating, these empty cracks are possibly produced by artificial desiccation of the material in the laboratory.

PART 2: PATTERNS OF WEATHERING
These irregularly distributed and parallel transverse fissures can be assigned to the category of transmineral fissures, although they are not clearly seen to extend through the neighboring minerals. Such regular orientation is indeed limited to the acicular crystals, whose particular orientation allows their easy breakage. Note that the fissures are not clearly observed in the neighboring crystals; their orientations make the transmineral fissures indistinguishable from the networks of fissures due to cleavages and other irregularities. This particular distribution of fissures and fractures is commonly observed in all crystals in which one dimension is far greater than the other two, as is the case for the needle-shaped, fibrous and acicular crystals of aegirine, acinolite, and apatite. Such transverse fissures also appear in crystals in which one dimension is much shorter than the other two, for example tabular and lamellar crystals of plagioclase.
A transmineral fracture cuts a feldspar grain by following one cleavage direction of the mineral. If the thin coatings are disregarded, it seems that the walls of the fracture are mainly accordant surfaces, and that the directions of the fracture are approximately at right angles to one another. These fractures are formed by lateral translation of the feldspar fragments. Their opening is not caused by dissolution, as the margins of the fragments are perfectly unweathered, at least at the scale observable with an optical microscope. A long transmineral fracture cuts grains of quartz and weathered feldspar in the granitic rock. It is probable that the fracture and its infilling have developed before the rock was weathered, because the width of the fracture remains constant whatever the host mineral. The infilling of the fracture is composed of mesocrystalline gibbsite, whereas the secondary gibbsite after feldspar is microcrystalline. Such infillings can promote appreciable enrichments of aluminum in fractured but unweathered rocks at the base of the ferrallitic or bauxitic profiles. It is obvious that the infillings are allochthonous, and that they have been formed by in situ crystallization from aluminum-rich solutions. Note that the quartz grains are not weathered.
A transmineral fracture runs across a grain of olivine that has been replaced by "iddingsite" during an early step of hypogene alteration. Many intraminnal cracks (protoclastic fractures) are still visible, and they appear as dark, curved, thin linearments coated with iron oxides derived from the oxidation of thin lamellar grains of magnetite. The reddish brown "iddingsite" is highly birefringent, and is homogeneously oriented according to the orientation of the original grain of olivine. Manganiferous solutions were transported over long distances along the transmineral fracture. Where they crossed an easily impregnated secondary material, such as "iddingsite", the solution irregularly diffused into and impregnated both margins of the transmineral fracture. Irregular hypocoatings are expressed by the local replacement of the usual bright red color of the "iddingsite" by black opaque areas. These displacements of manganiferous material and allochthonous concentrations are commonly observed during the weathering of basic and ultrabasic rocks, but the impregnation by these manganese hydrated oxides is more commonly observed in iron-rich materials, such as in "iddingsite" areas or in alteration morphs rich in iron oxyhydroxides. The other primary minerals of the rock, mainly clinopyroxene, are partially weathered to smectite which, even in proximity to the transmineral fracture, is not coated with hydrated oxides of manganese.
An intermineral fracture separates an unweathered rock into two fragments whose margins correspond to the external boundaries of the constituent grains. The original configuration of the open fracture has been partially obscured by the irregular illuviation of clay materials. The open fracture is partially infilled by coatings of smectitic material derived from the internal erosion of alteromorphs after pyroxene in the uppermost horizons of weathered rock. Both fragments are composed of the minerals usually observed in these rocks: clinopyroxene, hornblende and magnetite. All these primary minerals are unweathered. Along the intermineral fracture, some primary minerals have been partially weathered (A1, B2), the regular deposits have been partially eroded, and their more external layers have been degraded into brownish clay materials. As a reflection of the irregularities of the fracture and of its coatings, the intermineral pore has lost part of its regular shape, and is now converted into a chain of interconnected short pores. With continued infilling, parts of the intermineral fracture probably will be closed until the fracture is reopened as a result of later internal movements.

Part 2: Patterns of Weathering
When intermineral fractures are closely spaced and interconnected, rock fragments are isolated from one another. Where such fragments are mixed into the upper soil horizons, they are called lithorelics. The original rock is the same as in the previous photomicrographs, and the intermineral fractures and their coatings show the same patterns as the previous ones: irregularity of the fractures, irregular thickness of the coatings, constriction of the pores, and partial weathering of the primary minerals in grains that are located along both sides of the fractures.
Pyroxene crystals in this sample of equigranular clinopyroxenite have been separated by a regular network of intermineral fissures. These provided the pathways along which the isolated grains have been partially weathered to a yellowish saponitic secondary product. The weathering starts peripherally around each isolated crystal. The width of the banded intergranular material is relatively constant through the whole thin section. Cleavages of the pyroxene grains are enhanced by the beginning of the weathering; the finely denticulate shapes of the pyroxene remnants are clearly observed around the most strongly weathered grains (B2, D2), whereas the shape of the other slightly weathered grains (B-C 4-5) is not yet modified by any optically apparent denticulation. Most mineral grains are loosened by the network of fissures. Under these conditions, the nearly fresh rock loses its compactness and is rendered very friable, even though very limited quantities of secondary products have been formed.

**PART 2: PATTERNS OF WEATHERING**

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The rock contains clinopyroxene grains with an equigranular texture, grains of biotite altered to vermiculite (B1, B5, E5) during an earlier hydrothermal stage, irregular grains of magnetite, and small interstitial grains of apatite. All the clinopyroxene crystals have undergone a partial peripheral weathering to saponitic clay. The transformation of the biotite into vermiculite, with an appreciable increase in volume, has promoted the opening of many intermineral fissures and fractures. These, in turn, have promoted the subsequent peripheral weathering of the pyroxene crystals. The weathering starts along the intermineral pores: denticulate remnants of pyroxene are surrounded by progressively thicker and thicker rims of saponitic clay as the degree of weathering increases. The free circulation of water allows the pores to be widened, partially by internal erosion of the newly formed secondary clay, and partially by their own degradation into more iron-rich kaolinitic clay. True cutans of illuviation are not observed, but hypocoatings are developed around each alteromorph. Normally, in the lower horizons, the weathering of such iron-poor clinopyroxene induces the formation of very lightly colored saponitic clay. In the upper levels, the circulation of water allows the addition of iron, which enhances the coloration of the clay produced. Consequently, these upper alteromorphs differ from the lower ones, mainly in their chemical and mineralogical compositions: they are meta-alteromorphs.
057

**BASALTIC ROCK**
Morocco

Sampled by A. Dekayir
Depth: 0.4 m

Circum-mineral pore, artificial coloration

Objective: x 2.5
PPL

In the upper photomicrograph, an intermineral pore completely surrounds a pyroxene phenocryst and separates it from the weathered basaltic matrix. Where such an intermineral fissure or pore entirely surrounds a grain of a particular mineral, it is convenient to designate it as a circum-mineral fissure or pore. This pore has been partially infilled with allochthonous iron-rich material derived from the surrounding weathered matrix. The open part of the pore has been artificially infilled with colored synthetic material for better visualization of its volume, and also of the network of connecting of fissures and macropores along which the infilling material has been transported. Such circum-mineral pores are commonly observed where coarse-grained and hard bodies are embedded in a weathered matrix or soil material that can undergo important changes in volume under the alternating influences of humidity and dryness.

The lower photomicrograph shows a circum-nodular pore that surrounds a hard indurated alterrelic in a soft soil material. The pore exhibits a constant thickness; it is regularly coated by allochthonous infillings of clay material that delimit a chain of elongate empty pores in the median plane of the circum-nodular cavity.

058

**GRANITIC ROCK**
DagoliIè, Côte d'Ivoire
Sampled by B. Boulange
Depth: 1 m

Perinodular pore and clay coatings

Objective: x 2.5
PPL

PART 2: PATTERNS OF WEATHERING
A first step of hypogene alteration, a crystal of olivine has been partially replaced by an alteromorph of "iddingsite", still containing some small remnants of olivine. During a further step of weathering, the area converted to "iddingsite" lost magnesium and silica, and locally has been replaced by a homogeneous alteromorph of iron hydroxide. At this stage, the remnants of magnesium-rich olivine have been completely weathered, and have disappeared, leaving numerous intramineral pores now coated by iron oxides of relative accumulation. These coatings are clearly seen, under PPL, as dark reddish brown deposits surrounding each empty pore. The result of the combined effects of both hypogene alteration and supergene weathering is a polygenetic alveoporo-alteromorph. During a later stage of absolute accumulation of aluminum within the recently formed iron crust, the intramineral pores, derived from the dissolution of remnants of olivine, have been infilled by crystallaria of gibbsite, which are better observed under XPL. This last process gives rise to a polygenetic cumulo-alveoporo-alteromorph. The allochthonous origin of the gibbsite crystallaria is established by the fact that olivine does not contain aluminum. Note that the network of the original protoclastic fractures has been perfectly preserved during all these successive steps of transformation and accumulation.
prismatic crystals of clinopyroxene were completely enclosed within a large poikiloblastic crystal of phlogopite. During a first step of hypogene alteration, the phlogopite was altered to a meso-alteromorph of vermiculite, with considerable expansion perpendicular to the sheets of this layer silicate. This increase of volume is responsible for the fracturing of the embedded crystals of pyroxene; numerous open transverse intramineral cracks parallel the layering of the surrounding vermiculite. The plane of the thin section is conveniently oriented perpendicular to the layering of the layer silicate, and clearly shows the orientation of the resulting cracks. During a second stage, weathering of the pyroxene prisms preferentially started along these transverse intramineral cracks, and resulted in the development of denticulate remnants, now surrounded by saponite as a secondary product. All fragments of the pyroxene crystals have practically maintained their original crystallographic orientation, as shown by the homogeneous and uniform interference colors exhibited by all the fragments of each original prism.
A small crystal of orthopyroxene (hypersthene), whose pleochroism in shades of pink is rather characteristic, has been peripherally weathered to nontronite. The thickness (volume) of the nontronite-bearing rim is sufficient to promote important variations in volume under the influence of alternating conditions of humidity and dryness. These stresses, whose result is comparable to a process of colloid plucking, are responsible for the breakage of the grain of the precursor mineral into pieces by large concordant fractures, which will later be the pathways along which weathering will progress. In the example illustrated here, it is not the surrounding meso-alteromorphs that caused the breakage of the grain of orthopyroxene, as in the earlier illustrations, but its own rim of secondary products.
**PYROXENITE**
Koua Bocca, Côte d'Ivoire
Depth: 2.4 m

Complex assemblage of trans-, inter- and intramineral fissures

Objective: x 4
PPL and XPL

**TRANSMINERAL FRACTURES**

Orthopyroxene crystals, surrounded by clinopyroxene (A1, C-D-E5) and poikilitic hornblende, are crossed by numerous fissures, along which the orthopyroxene was partially altered hydrothermally to talc, associated with thin bands of secondary magnetite. The network of fissures is irregularly distributed. The fissures are interconnected, and are of three main types. Both orthopyroxene crystals are crossed by a common long transmineral fissure, whereas they are separated by a common intermineral fissure. The left-hand crystal exhibits numerous intramineral fissures, along which thin bands of talc are formed. The right-hand crystal is crossed by fissures of supergene origin, along which iron oxyhydroxides were deposited. The roundish crystals that are enclosed in the crystal of orthopyroxene on the right are interpreted as remnants of previously crystallized grains of clinopyroxene that were not completely resorbed during later growth of the orthopyroxene.
Patterns of alteration and weathering

Primary minerals may weather according to several simple or complex patterns, which are generally predetermined by internal and external factors. In practice, each mineral species weathers according to its own pattern. Without outlining all possible situations, it is necessary to use a simplified schematic classification of the most frequently observed patterns. More complex textures can be described by combining two or more simple patterns.

The weathering pattern observed in the weathered part of a mineral is mainly controlled by the nature of the primary mineral and by some of its characteristics. The proposed classification can be used as long as the original outline of the primary mineral is recognizable, and the volumes occupied by the three phases (residual mineral, secondary mineral and intramineral pore-space) are identifiable. The scheme is valid for all cases of simple or complex, partial or complete alteromorphs. It is also valid in the case where weathering is not exactly isovolumetric, i.e., where original shapes and volumes are only imperfectly maintained. In contrast, the scheme is no longer useful, without important modifications, to describe pedoplasmas, pedoturbed alteroplasmas, and other features in which the original textures are no longer identifiable.

Conservation of volumes

Depending upon the degree of preservation of the size and shape of the primary minerals as a result of their weathering, three main types of alteration and weathering patterns can be distinguished (Stoops et al. 1979):

Isomorphous alteration: The external shape and dimensions of the alteromorph are similar to those of the original mineral. The word “similar” is preferred to the word “identical”, because undetectable modifications of shape and size may have been produced during weathering. Such a weathering process promotes the formation of iso-alteromorphs (anheiral primary mineral) and of pseudomorphs (euhedral primary mineral).

Mesomorphic alteration: The external shape of the original mineral is well preserved and remains identifiable, but its volume has changed in one, two or three dimensions. These modifications are mainly caused by unidirectional expansion produced during the weathering of primary minerals that exhibit an appropriate structure, such as the phyllosilicates, or by multidirectional expansion recorded in secondary minerals such as the smectitic group of clay minerals. This weathering process promotes the formation of meso-alteromorphs.

Katamorphic alteration: The external shape and size of the original mineral are modified to such an extent that they are no longer identifiable. The mineral is partially replaced or divided, the relics or fragments are scattered, and their outlines become diffuse and indistinct. Only the mean position of the original mineral can still be recognized where the secondary products are not too dispersed. This results in the development of kata-alteromorphs.

In all cases, the entire grain of a primary mineral must be considered even if, during its weathering, it has been fractured into several residual fragments now scattered in its alteroplasma.

Penetration in a mineral: the pathways of weathering

The alteration patterns described below characterize not only iso-alteromorphs, but also meso-alteromorphs. The case of kata-alteromorphs is more complex, and can only be addressed by resorting to specific descriptions for each case.

A secondary mineral phase develops at the expense of a primary mineral phase following its planes and other areas of weakness. The main ones are: the external surface of the mineral, the open intramineral features (intramineral fissures, cleavage planes), and...
The closed surfaces of discontinuity (separation planes between adjacent minerals or inclusions).

The external surface of the mineral forms the bounding planes with the adjacent minerals. By definition, all bonds along the external surface are unsatisfied. Thus the surface layer is more reactive than the rest of the grain. Initially, these surfaces form only potential pathways of penetration. Under the influence of physical and chemical factors of near-surface origin, the suture interfaces are opened, and the weathering front, which exploits these planes, can penetrate the minerals in peripheral and centripetal ways even where the minerals do not exhibit any internal fissures or defects. These external surfaces are the most important pathways for incipient weathering of practically all primary minerals.

Surfaces of intermineral fissures cause the mineral to be divided into several potential contiguous fragments. Where open, these surfaces can be, to some extent, compared to external surfaces of the first type, because weathering progresses into each fragment from the periphery and in a centripetal manner. Some of these fractures and fissures may have been infilled by hypogene products of alteration and coated by hydroxylated minerals (chlorite in garnet, sericite in feldspar, amphibole in pyroxene, serpentine in olivine). In such cases, the description of the weathering of these composite minerals is made either by first considering the host mineral or by considering the mineral that weathered first. In any case, the entire mineral grain is considered, and not its separate fragments.

Cleavage planes divide the mineral by following one, two or even three parallel, orthogonal or oblique directions. They are responsible for the fragmentation of the mineral grain into small, regularly aligned polyhedral fragments. The cleavages are also to be considered as potential planes, which are later opened once the minerals enter the zone of the active weathering, for example. They may also open in thin sections of unweathered rocks, subjected to strong mechanical stresses during their preparation. Systems of planes, which correspond to poorly expressed cleavages, cut the mineral into irregularly shaped and sized fragments, each opened cleavage not necessarily being continuous throughout the whole grain. Stair-shaped open fissures are common. Where there is only one set of parallel cleavages, the mineral becomes divided into several layers, generally regular in shape, but of variable thickness in a direction perpendicular to these planes. Such a case of one perfect cleavage is exhibited by all phyllosilicates (e.g., muscovite, biotite, chlorite).

Closed surfaces along discontinuities of crystallographic (e.g., twin planes), mineralogical (e.g., separation planes and inclusions) and geochemical (e.g., zonation) origins, despite being very different from one another, produce comparable effects on the development of the weathering process and on the internal distribution of the alteromorphs. The influence of these surfaces of discontinuity is added to that of the cleavages and fractures, and thus increases the complexity of the alteromorphs and of their description. The closed surfaces of discontinuity are: twin planes, separation planes between adjacent minerals or inclusions, and concentric zonations.

Twin planes are situated between two or more individual crystals of the same mineral species present in different orientations in same grain. The twin law may lead to simple or polysynthetic, contact or penetration twins. Several different patterns of twins may coexist in the same grain (albite and pericline twins, for example, in a grain of plagioclase or microcline). A twin plane, if combined with oblique networks of cleavage on both sides, produces a distinctive "fish-bone" microstructure. This pattern is commonly observed during the first steps of weathering of elongate crystals of plagioclase in basaltic, trachytic and diabasic rocks, of orthoclase crystals in granitic rocks, or of twinned crystals of augite in some plutonic or effusive rocks. This specific distribution of symmetrically oriented cleavages with respect to the twin plane leads to the development of acantho-sepia-alteromorphs (see below).

Separation planes extend between lamellar or vermicular intergrowths and their host mineral. These planes separate distinct mineral species that generally exhibit a close affinity in their mineralogical or geochemical composition. The two different mineral species may exhibit very different patterns of behavior when subjected to weathering. Included in this group are perthitic intergrowths of microcline and albite in a K-rich feldspar, myrmekitic intergrowths of quartz in sodic plagioclase, lamellae of ilmenite in magnetite, symplectic intergrowths of magnetite and orthopyroxene, etc. Many separation planes of this type are closed systems because they are related to isolated inclusions, within the host mineral, without connection with the external pathways of weathering. Their pattern of behavior is similar to that of surfaces of contact between inclusions and the host mineral. These surfaces are closed and without connection with the exterior in cases where the inclusions are few, small and isolated. They play their role only where the host mineral is cut by intramineral or transmineral fissures. Otherwise, the separation surfaces have no influence on the weathering of the inclusions, but produce planes or areas of mechanical weakness. Apatite within quartz, acгрine in nepheline, and quartz in garnet are common examples of inclusions. Whether the
inclusion formed by exsolution, by a metamorphic reaction, or by accidental trapping during growth, seems "secondary" to the whole issue. If inclusions of weatherable minerals are completely entrapped in a practically unweathered mineral, they can persist unweathered until they reach the upper part of the profile.

Concentric zones resulting from continuous or discontinuous chemical variations during growth are typical of solid-solution series. One of the zones may be rather more weatherable than the other, and it can promote, when weathered, the formation of a concentric banded pattern, in which bands of weathered material alternate with bands of residual mineral. The development of a weathered central core may induce the later fragmentation, by a radial network of fissures, of the more resistant residual rim. Some of the most commonly observed examples include zoned plagioclase whose central part is more calcic and more weatherable than is the more sodic, external part. Zoned crystals of olivine show a relative enrichment of the forsterite component in the core, and of the fayalite component in the rim. Zoned augite also shows a predictable rimward enrichment in the ferrosilite component over the enstatite component.

Parallel alternation of interlayered phyllosilicates of distinct chemical composition and different weatherabilities are rather common. This alternating arrangement, combined with the perfect cleavage of these minerals, promotes the weathering of the most resistant species by inducing deformations in the first-formed secondary products formed at the expense of the less resistant species. Some examples include grains composed of alternating layers of primary biotite and primary muscovite, primary biotite and chloritized biotite, etc. The more resistant muscovite or chlorite commonly is broken into small pieces by the stresses generated by the smectite-group phase developed at the expense of the less resistant biotite. The intercalation of microcrystals between the layers of some micas can play the same role in the weatherability of the whole grain. Consider, for example, lenticular inclinations of titanite and calcite between layers of biotite and chlorite, and the sogenitic rutile and goethite microcrystals regularly interlayered in a biotite grain.

**Descriptions and Classification**

The secondary minerals that progressively develop at the expense of the primary minerals under the influence of near-surface weathering exhibit specific patterns of organization, which are influenced by the nature, distribution, orientation and density of planes of weakness in the original minerals.

During the first steps of weathering, the organization of the alteration textures remains strongly related to the network of planes and areas of weakness, inherited from the original mineral. Thereafter, with the formation of new fissures, of irregular dissolution-related pores, with the thickening and the multiplication of the secondary microstructures and with the development of recrystallization, new textures appear away from the original sites. In spite of these progressive modifications, the original microstructures persist for a long time, and remain identifiable until the ultimate stage of weathering, when alteroplasmas have completely replaced the original minerals. The persistence of the primary patterns of organization in the levels of complete weathering amounts to a signature, and allows the identification of the parent minerals and, so, the identification of the parent rock, even if it has not been reached at the base of the profile selected for sampling.

The classification and the systems of description to be presented below follow a preliminary attempt (Stoops et al., 1979) and a more recently proposed terminology (Delvigne, 1994) that specifically focuses on the completely developed alteromorphs. This most recent attempt has been refined and is presented in Part 3 of this book.

**Pellicular pattern of organization**

In minerals that do not exhibit fractures or directions of good cleavage, the organization of weathering features is of a pellicular type (Figs. 5, 6). It starts from the borders of the mineral and follows the intermineral boundaries. Weathering proceeds centripetally all around the mineral grain and gradually extends toward its central part. It surrounds a residual core (or nucleus), whose size progressively decreases. Three main cases can be distinguished.

- Weathering transforms the original mineral into secondary products whose volume nearly corresponds to the volume of the original mineral. Most chemical elements of the parent mineral are incorporated into the structure of the secondary products. There is no empty space, or very little, around the residual core. Once the weathering is complete and the residual mineral has disappeared, a full iso-alteromorph is formed. It is a holo-alteromorph (or, more precisely, a holo-iso-alteromorph). Where the primary mineral is an automorphic mineral, the alteromorph that results from its weathering is a pseudomorph. Examples include the transformation of olivine to "iddingsite", the
FIGURE 5. PELLIcULAR PATTERNS OF WEATHERING.

A. Regular pellicular pattern
0: euhedral crystals of pyrite;
1: thin pellicular rim of iron oxyhydroxides;
2: thick pellicular rim of iron oxyhydroxides surrounding large residual cores;
3: nearly complete weathering and small residual cores;
4: complete weathering to iron oxyhydroxides: HOLO-PSEUDOMORPH.

Note: Concentric laminations commonly are visible within the rim of secondary products; these are the traces of the successive stages of weathering. Microlaminated alternations of hematite - goethite are observed in some instances; in this case, a two-phase holopseudomorph results. The weathering of such euhedral crystals leads to the formation of true pseudomorphs.

B. Irregular pellicular pattern
0: anhedral crystal of clinopyroxene;
1: thin pellicular rim of a secondary smectite-group mineral;
2: thick pellicular rim of well-oriented smectite and large denticulate residual core;
3: nearly complete weathering to well-oriented smectite and small denticulate residues;
4: complete weathering to well-oriented smectite without visible internal pores: HOLO-(ISO)-ALTEROMORPH.

Note: Where the plane of the thin section is (nearly) parallel to the $Z$ axis of the pyroxene, the optical orientation of the smectite is uniform and continuous throughout the alteromorph, and the orientation of the denticulation of the pyroxene residues is parallel to that of the general layering of the smectite particles.

C. Irregular pellicular pattern
0: anhedral crystal of orthopyroxene;
1: thin pellicular rim of a secondary smectite-group mineral;
2: thick pellicular rim and large residual core separated by thin circumnodular residual void;
3: nearly complete weathering to oriented smectite with minute residues rimmed by thick residual voids;
4: oriented smectite and irregular pores developed from the last residues: (ORTH0)-ALVEOPORO-ALTEROMORPH.

Note: In an ortho-alveoporo-alteromorph, as shown here, the shape of the residual pores is denticulate and similar to the shape of the residual cores that have disappeared, in a para-alveoporo-alteromorph, their shape is rounder and smoother because the pores, rimmed by late iron oxyhydroxides, develop by further degradation of the previously formed smectite-group mineral.
FIGURE 6. PELLICULAR PATTERNS OF WEATHERING.

A. Combined with a linear pattern
0: subhedral crystal of biotite containing an inclusion of prismatic apatite;
1: incipient weathering of the biotite to vermiculite with a small increase in volume;
2: advanced weathering of the mica, further increase in volume, and fracturing of the apatite inclusion;
3: nearly complete weathering, with formation of parallel phyllopores and displacement of the fractured inclusion;
4: oriented vermiculite and parallel lenticular phyllopores: PHYLLOPORO-(MESO)-ALTEROMORPH.

Note: Where the prismatic inclusion is not exactly perpendicular to the layering of the mica, the transverse fractures that segment the inclusion, owing to the volume increase of the host mineral, also allow a lateral displacement of its fragments. The fracturing and dislocation of the included minerals strongly increase their weatherability.

B. Combined with a linear pattern
0: subhedral crystal of biotite;
1: incipient weathering to kaolinite starting on and extending mainly from opposite sides;
2: thin layers of kaolinite interlayered with thick residual cores of biotite;
3: thick layers of kaolinite showing expansion of their lateral edges, opening of pores, and appearance of minute opaque inclusions;
4: oriented kaolinite and large lenticular pores: PHYLLOPORO-(MESO)-ALTEROMORPH.

Note: The iron content of the primary biotite is expressed by minute crystals of goethite distributed parallel to the kaolinite layers and concentrated within the central part of the alteromorph. The lenticular pores are not true residual pores, but rather pores opened under the influence of mechanical forces developed as a result of the expansion of the weathered mineral.

C. Combined with a linear pattern
0: subhedral crystal of biotite;
1: incipient irregular weathering to a smectitic clay;
2: irregular distortion of the primary and secondary minerals due to the swelling process;
3: remnants of the primary mineral and secondary products are highly fractured and contorted, with the opening of many irregular pores;
4: irregular, highly fractured and disjoined alteromorph: KATA-ALTEROMORPH.

Note: The replacement of micaceous minerals by vermiculite or kaolinite is accompanied by a regular increase in volume, which induces the formation of meso-alteromorphs; swelling smectitic clays generally induce the formation of kata-alteromorphs. The iron content of the biotite commonly is accommodated in the structure of the smectite.
weathering of pyrite crystals into iron oxyhydroxides (Fig. 5A) and of clinopyroxene into a smectite-group mineral (Fig. 5B).

- Weathering progresses in the same way, but an empty pore is rapidly formed, as a rim around the residual core (inter-plasma = mineral pore or perinuclear pore). The width of the pore increases progressively as the volume of the original core decreases. The volume of the final pore is proportional to the volume of the exported chemical elements, which do not contribute to the development of the alteroplasma. The external rim of alteroplasma becomes thicker and thicker owing to centrifugal nanoscale transfers of elements from the core to the rim. Once the weathering is complete, a continuous corona of alteroplasma surrounds a resid­

ual empty pore, whose borders are more or less parallel to and concentric with the original intermineral contact-surfaces. They are porous or pore-bearing alteromorphs (group of the pore-alteromorphs: Fig. 5C). Where the alteromorph shows only a large central pore, it is a centropore-alteromorph. This is the pattern of weathering of most unfractured and uncleaved, rela­

tively small-sized grains of silicate minerals.

- Weathering still progresses in the same way, but with the complete congruent removal of all the chemical elements of the primary mineral. No secondary alteroplasma is formed in situ, and the size of the residual core progressively decreases, with formation of only empty perinuclear pores. Where the weathering is complete, an empty alteromorph is formed (koilo­

alteromorph). The shape and size of the primary minerals are temporar­

ily maintained if the adjacent primary minerals are not weatherable minerals, if they are not yet weathered, or if they have given rise to mecha­

nically resistant alteroplasmas. Rocks that are rich in solu­

ble minerals generally lose their original structures when undergoing weathering. Koilo-alteromorphs are commonly formed by the weathering of very soluble minerals such as calcite, gypsum, apatite and, under exceptional conditions, quartz. The term can be extended to nearly empty alteromorphs whose (primary or secondary) mineral content does not exceed 2.5%.

- Pellicular patterns are commonly combined with other patterns of weathering, such as linear pat­

terns (Fig. 6). Practically all primary minerals exhibit a pellicular pattern during their incipient weathering, whatever the subsequent progress of weathering toward the grain’s interior.

Linear and banded patterns

During the weathering of minerals, networks of fractures and cleavages play the same role as the inter­

mineral surfaces previously described. Each part of the fragmented or cleaved mineral, if isolated in these networks, reacts individually to the weathering process, and each of them is surrounded either by alteroplasmas or by empty pores. In descriptions of this pattern of weathering, the original mineral must be considered in its totality, whatever the extent of its division into smaller fragments.

If the primary mineral is weathered to alteroplasma without development of inter-plasma — mineral pores, all the unweathered remnants within their matrix of secondary products maintain not only their position and their alignment, but also their crystallographic orientation. All the residual fragments of the crystal considered go simultaneously to extinction (or do so in groups if the crystal is twinned) by rotation of the microscope stage with crossed nicols. In contrast, where large empty pores are developed between the primary mineral and the secondary phases, the remnants may maintain their position and their alignment, but generally they may partly or completely lose, by rotation, their common and uniform crystallographic orientation.

Primary minerals that lose only a small part of their constituent elements, and that as a result do not develop identifiable pores once completely weathered, normally give way to holo-alteromorphs, which can be distinguished from the holo-alteromorphs previously described ( peripheral patterns) only by the visible traces of the original networks of fractures and cleavages. These traces are in some cases emphasized either by deposits of different materials, or by differences in size, orientation or crystallinity of the particles of alteroplasma, which are distributed along these traces.

In general, within the fractured or irregularly cleaved minerals, weathering follows these planes preferentially. The secondary products are distributed along them, first as a linear irregular pattern, and later as a banded irregular pattern where, with increasing weathering, the thickness of the secondary products formed along the planes has increased (Fig. 7A). The residues of the unweathered primary mineral are irreg­

ularly distributed (random residues), and their size gradually decreases, the smallest residues generally
Figure 7. LINEAR PATTERNS OF WEATHERING.

A. Regular (parallel) linear pattern

0: subhedral crystal of biotite;
1: incipient alteration to chlorite along the cleavage; thin layers of chlorite develop through the crystal;
2: chlorite is distributed in a regular parallel banded pattern alternating with organized residues of biotite;
3: organized thin layers of residual biotite are enclosed in the chlorite;
4: complete alteration of biotite to chlorite: ISO-ALTEROMORPH.

Note: The first series of drawings illustrates the case of alteration of a primary micaceous mineral to a chlorite without increase of volume; as a result, shapes of the original grains were maintained. This type of alteration, without volume increase, is less commonly observed than the next one.

B. Regular (parallel) linear pattern

0: subhedral crystal of biotite;
1: incipient alteration to chlorite along cleavage planes; thin layers of chlorite develop through the crystal;
2: layers of chlorite and residual biotite are equally distributed, but the increase in volume is perceptible;
3: organized thin layers of residual biotite and thick layers of chlorite alternate;
4: complete alteration of biotite to chlorite with regular increase of volume: Meso-ALTEROMORPH.

Note: The second series of drawings illustrates the case of alteration of a primary micaceous mineral with appreciable but regular increase of volume in a direction perpendicular to the layering of the mice; the external form of the primary mineral is easily recognized, but the dimensions have changed in one direction.

C. Regular (parallel) linear pattern

0: regularly cleaved crystal of pyroxene whose Z axis is parallel to the plane of the thin section;
1: incipient weathering to goethite along part of its rim and its cleavage;
2: thin pellicular (peripheral) and parallel linear weathering; large denticulate residual cores of primary pyroxene;
3: thick pellicular and parallel banded patterns and organized minute denticulate residues of primary pyroxene;
4: complete weathering to a regular boxwork of goethite: REGULAR (PARALLEL) SEPTO-ALTEROMORPH.

Note: The thickness of the septa and the size of the residual voids are closely related to the original iron content of the primary mineral. Once the minute residues are completely isolated within a large circum-nodular residual void, they can lose their common orientation and their simultaneous extinction in XPL.
disappearing before the largest ones. Good examples of random residues surrounded by an irregular banded network include partial serpentinization of an olivine crystal (fractured mineral) or partial replacement of K-feldspar (irregularly cleft mineral) by secondary plasmas. Upon completion of weathering, in the most common case of thorough leaching of the original constituents, an alveoporo-alteromorph is developed, which is irregularly intercollected bands, between which irregularly shaped pores have replaced the last-removed primary residues.

Where the banded networks of alteroplasma or crystallplasma exhibit a constant thickness (septa) and where they surround empty pores whose total volume is greater than the volume of the secondary products, an irregular septo-alteromorph is developed ("box-shaped" irregularly shaped pores have replaced a last-banded layer of secondary material whose composition consists of random residues surrounded by an irregular banded network of secondary material whose composition is similar to that of the internal septa.

In minerals that show a regular and continuous network of well-expressed parallel or crossing cleavages, the weathering products are regularly distributed along this network. During the first step, they are distributed according to a parallel- or cross-linear pattern, which later evolves into a parallel- or cross-banded pattern. The unweathered residues are also organized into parallel alignments (organized residues); each of them is situated in the central part of a cell of the linear or banded network.

An example of the parallel banded pattern is given by the weathering of mica- and chlorite-group minerals (one set of parallel cleavages: Fig. 7A, B), whereas examples of regular parallel, linear- or banded patterns are also given by the weathering of pyroxene- and amphibole-group minerals, where crystals have been cut parallel to their Z axis (one apparent set of cleavages in the plane of the thin section: Fig. 7C).

An example of the irregular cross-linear pattern is given by the weathering of an olivine crystal whose irregular protoclastic fractures are the pathways for the incipient weathering of the crystal (Fig. 8A) or by the weathering of an irregularly fractured crystal of garnet to iron oxyhydroxides (Fig. 8B).

An example of the regular cross-linear or cross-banded pattern is illustrated by the weathering of a grain of amphibole (Fig. 8C) or pyroxene (two sets of oblique or suborthogonal cleavages), which is distinctly seen in crystals whose Z axis is perpendicular or oblique to the plane of the thin section; this pattern gives rise to regular septo-alteromorphs.

It seems evident that not all the cleavages of a mineral always appear distinctly in the thin section. Thus they can be incomplete, discontinuous or interrupted. This factor determines the formation of a more or less complete network of lines, bands and septa whose segments are mostly arranged according to idealized linear or crossed patterns. Other particular symmetrical linear or crossed patterns result from the weathering of twinned minerals.

An example of the incomplete regular cross-linear pattern is given by the weathering of a crystal of orthoclase that exhibits partly developed cleavages (Fig. 9A). An example of a symmetrical linear pattern is seen in the weathering of a twinned mineral (pyroxene or feldspar, for example) whose cleaved parts are symmetrically arranged on both sides of the twin plane (Fig. 9B).

Irregular patterns

A last case is shown by minerals in which no fractures or cleavages are developed and whose weathering develops in an apparently random way, without evident controls on direction or orientation by internal or external factors.

A first irregular pattern of weathering occurs where the breakdown starts peripherally and invades the mineral following irregular and interconnected digitate lineaments (Fig. 9C). These are progressively widened (banded) and connected, leaving irregular isolated residues of the primary mineral. This pattern is common in the weathering of apparently unfractured or poorly cleaved minerals such as feldspars.

A second, very common, pattern of weathering occurs at the beginning of weathering, when the secondary products and associated pores are developed as randomly distributed specks (spikelled pattern) within the mineral. The size of these specks progressively increase, joining together forming patches (patchy pattern) at a more advanced stage of weathering (Fig. 10A, B). The primary mineral is progressively corroded, divided into several irregular fragments (randomly distributed cavernous residues). The size of these fragments progressively decreases (dispersed minute residues) until they disappear from the completely developed alteromorph. Such is
A. Irregular linear pattern
0: euhedral crystal of olivine crossed by intramineral protoclastic fractures;
1: linear weathering of the olivine to nontronite along part of its fractures and boundaries;
2: irregular banded pattern with random residues; iron oxyhydroxides appear along the fractures;
3: small coarsely denticulate residues within the nontronite, part of which is oriented, mainly along the fractures;
4: complete weathering of olivine to nontronite clay: HOLO-(ISO)-ALTEROMORPH.

Note: If the original crystal is largely fractured, the clay particles commonly are strongly oriented along its outer edges and along both sides of the fractures, whereas the inner volumes are filled with randomly oriented and homogeneous secondary clays. No differences in composition are recorded between the oriented and the random particles.

B. Irregularly crossing linear pattern
0: unclose but irregularly fractured euhedral crystal of garnet;
1: incipient linear weathering along part of the edge and along fractures in the crystal;
2: irregular cross-banded pattern of goethite, enclosing random residues surrounded by residual voids;
3: randomly distributed minute residues and many residual voids within an irregular network of goethite septa;
4: complete weathering to an irregular boxwork: IRREGULAR SEPTO-ALTEROMORPH.

Note: The richer in iron is the garnet, the thicker the septa of goethite and the smaller are the residual voids. In the case of euhedral crystals, the completely weathered grains of garnet give rise to irregular septo-pseudomorphs. Manganese oxide deposits or minute crystals of gibbsite commonly are observed in the alteromorph after Mn-rich or Al-rich garnet, respectively.

C. Regularly crossing linear pattern
0: well cleaved euhedral crystal of hornblende;
1: incipient linear weathering along part of the crossed cleavages, leaving narrow residual voids;
2: regular cross-banded pattern of goethite (boxwork), organised residues and residual voids;
3: organised minute residues of primary mineral isolated within a regular boxwork of goethite;
4: complete weathering to a regularly crossing boxwork: REGULAR (CROSSED) SEPTO-ALTEROMORPH.

Note: During the first stages of weathering, all the denticulate residues maintain their original orientation and their simultaneous extinction. Once completely isolated and free to move within their cells, they lose their original orientation, and their extinction, in XPL, no longer is simultaneous throughout the alteromorph.
FIGURE 9. LINEAR PATTERNS OF WEATHERING.

A. Regularly crossing linear pattern
0: cleaved anhedral crystal of orthoclase; few cleavages appear in the unweathered mineral;
1: incipient linear weathering to an isotropic secondary material along a part of the rim and along the cleavages;
2: regular cross-banded pattern in the secondary material and organized cavernous residues of primary feldspar;
3: nearly complete weathering to isotropic material, and few organized minute residues of primary feldspar;
4: complete weathering and further evolution to kaolinite: GRADUAL POLYPHASE ALTEROMORPH.

Note: The isotropic material is an intermediate phase that commonly develops between the feldspar residues and the kaolinite minerals; these appear as end-products of the weathering under restricted or normal conditions of weathering. Traces of the original cleavages are partly enhanced by thin deposits of iron oxyhydroxide of allochthonous origin.

B. Regular symmetrical linear pattern
0: twinned and cleaved orthoclase; cleavages are necessarily symmetrically oriented on both sides of the twin plane;
1: incipient linear weathering to crystals of gibbsite and organized cavernous residues of primary feldspar;
2: regular symmetrical banded pattern of crystalline gibbsite and organized cavernous residues of primary feldspar;
3: advanced weathering; symmetrically banded pattern of gibbsite and minute residues surrounded by large residual voids;
4: central septum and symmetrical septa enclosing large residual voids: ACANTHO-SEPTO-ALTEROMORPH.

Note: Under conditions of efficient leaching, feldspar-group minerals commonly weather directly to gibbsite without passing through an intermediate phase of isotropic material. The leaching of alkalis and silica is complete; the volume of residual voids may be larger than that of the secondary minerals.

C. Irregular digitate pellicular pattern
0: anhedral crystal of feldspar;
1: incipient weathering to isotropic material according to a pellicular and irregular digitate pattern;
2: irregular cores within isotropic material (IM); small dots: recently formed IM, larger dots: early-formed IM;
3: the first-formed part of the IM is replaced by gibbsite crystals according to an irregular-digitate banded texture;
4: early-formed septa of gibbsite associated with recently formed gibbsite: GLOMERO-SEPTO-ALTEROMORPH.

Note: The chemical composition of the isotropic material, which is intermediate between the feldspar and gibbsite, is gradually modified with aging; the early-formed parts of IM are consequently the first ones to be replaced by gibbsite. Feldspar residues, IM and gibbsite can temporarily coexist.
FIGURE 10. SPECKLED AND PATCHY PATTERNS OF WEATHERING.

A. Irregular speckled pattern

0: irregularly fractured crystal of plagioclase;
1: irregularly speckled pattern of isotropic secondary products along part of the intramineral fractures;
2: irregular patchy pattern of the secondary material and large cavernous residues of primary mineral;
3: advanced stage of weathering, with further development of the secondary material and dispersed minute residues;
4: complete weathering to isotropic material before kaolinite has developed; Holo(ISO)-ALTEROMORPH.

Note: As early as stage 2, the isolated specks and patches of the secondary material begin to coalesce, and give way to a continuous secondary phase in which coarse or minute cavernous residues are isolated. Traces of the original fractures may be partly enhanced by allochthonous deposits of iron oxyhydroxides.

B. Regular speckled pattern

0: orthoclase crystal with few regular opened cleavages, which are pathways for the development of small specks of secondary material;
1: the early-formed specks coalesce along the cleavages and form regularly crossing elongate patches;
2: most patches form a continuous phase of isotropic material in which organized cavernous residues are distributed;
3: nearly complete weathering: dispersed minute residues randomly distributed in a homogeneous secondary phase;
4: the residues disappear, and kaolinite forms from the secondary phase: GRADUAL TWO-PHASE ALTEROMORPH.

Note: This case, very similar to the previous one, is distinguished from it by the internal distribution of the first-formed specks and the later patches of secondary products. The development of the kaolinite in this example can also occur in the previous one, since it is evidently not related to the regularity or irregularity of the fractures or cleavages.

C. Concentric speckled pattern

0: zoned crystal of plagioclase, whose zonation is expressed by the linear and concentric development of inclusions;
1: specks and patches of secondary material are developed mainly in the central (more calcic) part of the feldspar;
2: patches of secondary material are enlarged and coalesce, with replacement of most of the central zone;
3: the digitate central patch of secondary products is surrounded by an irregular residual rim of the primary mineral;
4: crystals of kaolinite develop in the central part (the first-formed) of the intermediate isotropic material.

Note: Where alteromorphs still contain both intermediate isotropic material and kaolinite, it is more suitable to classify them as gradual two-phase alteromorphs. Where the isotropic material has disappeared, it is more objective to classify them as holo-(iso)-alteromorphs (or botryo-alteromorphs if crystals are isolated, with interconnected voids between them).
the case, for example, in the weathering patterns of most feldspar crystals, whatever their replacement phase, be it gibbsite, kaolinite, halloysite or isotropic, amorphous material.

A third example is given by the weathering of zoned crystals, whose more weatherable central parts are attacked before the outer parts. This concentric pattern is illustrated by the weathering of zoned crystals of plagioclase (Fig. 10C).

**Complex patterns**

Most patterns described above may combine with one another to give complex patterns of alteration. They can be described by combining a number of more simple patterns. The most common situations are those in which several distinct patterns are juxtaposed side by side or superposed one upon the other. They develop from the combination of sets of irregular fractures and regular cleavages or twin planes and from the combination of internal zonations and sets of fractures or cleavages.

A classical example is provided by the weathering of coarse-sized crystals of pyroxene, which are fragmented into several parts by transmineral or transverse fractures. During the first stage of weathering, the distribution of the secondary mineral (such as, for example, the smectite-group mineral that develops under conditions of restricted drainage) is related to the network of fractures. The smectite-group phase is distributed in an irregular banded pattern. Thereafter, during a more advanced stage of weathering, each isolated but unfractured fragment of the primary mineral is weathered in a regular parallel or cross-linear pattern, which is related to the number and directions of the original cleavages.

The crystallographic orientation of minute secondary particles is also related to specific crystallographic directions in the original mineral. All these crystallites are oriented parallel to the $Z$ axis of the pyroxene crystal, and, thus, independently of the fractures and of both sets of cleavages if these are simultaneously and distinctly observed in the alteromorph. If only one set of cleavages is apparent (as in the case of crystals whose $Z$ axis is parallel to the plane of the thin section), the secondary particles are oriented parallel to the cleavage. Their straight extinction is then simultaneously observed in the whole alteromorph; it will be either simultaneous and parallel to the extinction of the pyroxene residues in the case of the weathering of an orthopyroxene crystal (straight extinction), or not simultaneous and oblique to the residues if the weathered mineral is a clinopyroxene (oblique extinction).

These differences in angle of extinction between the smectite particles on one hand, and the residues of pyroxene on the other, constitute an additional criterion for identification of the parent material where the residues are too small for normal determination by optical methods.

Where the alteromorph is completely developed, traces of the first fractures can still be identified if intramineral pores (strong leaching) or iron oxyhydroxides (differential weathering or absolute accumulation) were formed at their contact. The complexity of such alteromorphs can still increase by later weathering, either of residues of pyroxene or of the smectite-bearing secondary products, as will be shown below.

*In summary, the different possible patterns are:*

- **Regular**
  - Pellicular patterns: mainly controlled by intermineral discontinuities and mineral interfaces,
  - Linear (or banded) parallel or crossed patterns: mainly controlled by intramineral factors, such as well-expressed cleavages, twin planes and crystallographic directions, or
  - Zoned patterns: with concentric distribution of the secondary products mainly controlled by intramineral chemical variations;

- **Irregular**
  - Linear (or banded) patterns: mainly controlled by transmineral and protoclastic fractures in uncleaved minerals,
  - Speckled and patchy patterns: mainly developed within the mineral without any apparent relationship with its crystallographic structure, or
  - Complex patterns: resulting from the combination of several simpler regular or irregular patterns.
A euhedral crystal of olivine has been partially altered to "iddingsite" during cooling of the basalt. The peripheral alteration progresses centripetally from the edge of the grain. Had the alteration process continued to completion, the euhedral crystal would have been completely transformed to a true pseudomorph of "iddingsite". The original crystal’s faces have remained undisturbed during and after the transformation. The groundmass of the basaltic rock is not altered; it contains lath-shaped grains of plagioclase, small interstitial grains of clinopyroxene, grains of magnetite, and small crystals of olivine that also have been partially transformed to "iddingsite".

**Basaltic Rock**
Morocco
Sampled by A. Dekayir
Depth: 2 m
Regular peripheral pattern of alteration around a euhedral phenocryst of olivine
Objective: x 10
PPL and XPL
Most clinopyroxene grains of this equigranular clinopyroxenite are separated by a regular network of open intermineral fissures, along which peripheral weathering has begun. Most grains of clinopyroxene are surrounded by a thin rim of a secondary product of saponite composition. The fine denticulation, which normally develops around residual cores, has not yet appeared around most grains; the weathering reaction has not progressed sufficiently to allow such a feature to be clearly observed at the scale of the optical microscope (compare with photomicrographs 054, 055).
The carbonatite rock is essentially composed of carbonate minerals, which exhibit a granular texture, with variable quantities of accessory minerals such as apatite, opaque minerals (magnetite, perovskite), micas, clinopyroxene, olivine, monticellite and clinohumite. The dominant carbonate mineral is generally calcite, but it may contain variable amounts of magnesium and iron. The photomicrograph shows the first step in the weathering of such a rock; it starts along the intermineral suture planes, giving way to a regular peripheral pattern of weathering. The primary calcite is progressively dissolved. Complete dissolution will be responsible for the formation of kollo-alteromorphs (see later), whose original borders are in some cases emphasized by residual deposits of oxyhydroxides derived from the insoluble iron content of the precursor. Note that as soon as they begin to weather, the primary minerals quickly adopt a denticulate shape, which progressively will increase (see the two next illustrations, 072 and 073) with concomitant thickening of the residual deposits of the insoluble components. Two crystals of apatite are recognizable, in A-B2, by their first-order grey interference-color in XPL. Note that these slightly more resistant minerals do not undergo any peripheral weathering; their outer surface is not denticulate.
**072, 073**

**CARBONATITE**
Juquia, SP, Brazil
Sampled in a quarry by A.V. Waiter

Regular peripheral pattern of weathering around grains of calcite

Objective: × 6.3
PPL and XPL

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The photomicrographs were taken from the same sample as in the previous example, and show the weathering front. The upper left-hand corner corresponds to the weathered part of the rock, and the lower right-hand corner, to the unweathered rock. Note the differences shown by the intermineral suture planes, which are only slightly emphasized by very thin deposits of colored material in the unweathered part of the rock. In contrast, the regular denticulation is well developed around each partially dissolved grain of calcite. Although not obvious in this photomicrograph, the orientation of the denticulation is related to the crystallographic orientation of the primary crystal. Note the thickening of the residual deposits of iron oxyhydroxides, derived from the in situ crystallization of the insoluble iron content of the calcite, the widening of the intermineral residual pores, which will promote the formation of (quasi-) empty koilo-alteromorphs (see later, 285 and 286), and the relative resistance of the apatite grains in the weathered part of the rock. This differential behavior of the calcite and apatite promotes the formation of highly concentrated relative accumulations of residual apatite, which makes the weathered rock an economically interesting phosphate-rich layer.

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**PART 2: PATTERNS OF WEATHERING**
Patterns of alteration

**074**

**AMPHIBOLE-BEARING CLINOPYROXENITE**

Koua Bocca, Côte d'Ivoire

Sampled at outcrop

Regular peripheral pattern of weathering around pyrite

Objective: \( \times 10 \) XLP

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**075**

**GABBRO**

Cataguases, MG, Brazil

Sampled by L.M. Lopez

Depth: 4 m

Irregular peripheral and internal linear patterns in titaniferous magnetite

Objective: \( \times 6.3 \) XLP

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A typical grain is partly oxidized to a peripheral cortex of iron oxyhydroxide, which centripetally invades the opaque core of the mineral. The thickness of the peripheral cortex is somewhat regular all around the residual grain. Note that the cortex closely surrounds the core, and that no intermediate pore is observed. The primary mineral in the core is more or less protected from continued weathering by this protective layer. This phenomenon generally occurs where the ratio of molar volume of the secondary mineral to that of the primary mineral is equal to or greater than 1. The regularity in thickness of the peripheral cortex is due to the lack of intramineral defects in the primary mineral. Such is not the case in this second example of weathering of an opaque mineral (titaniferous magnetite), which is crisscrossed by numerous twin planes, lamellar intergrowths and intramineral fractures. The peripheral pattern of weathering loses its regularity, and penetrates the primary mineral along all its planar defects. The secondary products contain both Fe and Ti oxides. In the upper right-hand corner of the photograph, an associated grain of ilmenite has been completely weathered to yellowish brown cryptocrystalline anatase. The surrounding grains of feldspar are completely weathered to gibbsite.
Almandine (garnet group) is embedded in a granitic gneiss whose main mineral constituents are quartz, alkali feldspar and plagioclase, with biotite and accessory muscovite as the micaceous minerals. All these minerals are regularly oriented and distributed, giving the rock a typical layered texture. Note that the foliation tends to wrap around the grain of garnet. The peripheral weathering of the garnet has given way to the formation of an irregular rim of iron oxyhydroxides, but this rim seems to be formed not as a true rim closely bonded to the external surface of the residual core, but as a detached rim formed by diffusion and impregnation of the surrounding micaceous minerals by the iron compounds released by weathering of the garnet. The volume of the pore is related to the volume of the portion of primary mineral that was weathered. Note that garnet-group minerals have a cubic symmetry and that, consequently, they are isotropic and at extinction in XPL. Some quartz inclusions are randomly distributed within the garnet porphyroblast.
A piece of olivine is partially altered to "chlorophacite" under deuteritic conditions. The secondary phase is the isotropic bright yellow material that surrounds the olivine core. The secondary product is mainly peripherally distributed around a very irregular core, whose margins are coarsely denticulate. Since the material is isotropic, it is not possible to test for concordance between the orientation of the olivine core and that of the "chlorophacite" rim. The "chlorophacite" usually exhibits this bright yellow color in PPL, but it may vary in color from bright orange to deep green, and in index of refraction, from 1.50 to 1.62. "Chlorophacite" is not a very common product of alteration of olivine, but is used here to illustrate an irregular peripheral pattern of alteration. Silica, iron oxide and H₂O are its main constituents. The other components of the rock, clinopyroxene, plagioclase and magnetite, are generally not, or very slightly, affected by such a hypogene process.
Patterns of alteration

A thin, irregular and discontinuous rim of an isotropic secondary product is developed around this euhedral crystal of plagioclase. The secondary product is easily distinguished in PPL by its yellowish color, which is due to impregnation with iron-rich compounds, similar to those that appear within the inter- and intramineral fissures of the surrounding rock. The isotropic character of the secondary product is clearly seen in XPL. The isotropic rim contrasts strongly with the unweathered grey twinned crystal. Note that the internal border of the rim is highly irregular, and that the products of weathering irregularly penetrate the residual core along digitating and branching fissures. With increasing degree of weathering, the thickness of the isotropic rim gradually increases, the rim material will penetrate the core along irregular fissures, isolating small residues randomly distributed within the secondary phase. The isotropic material will replace most of the primary core, and remain until it is itself replaced by secondary crystalliplasmas whose mineralogical composition (kaolinite or gibbsite) will depend on the local conditions of weathering and leaching.
Kersantite
Brittany, France
Sampled in a quarry by E. Bernabe
Particular case of a peripheral pattern of alteration around biotite

Objective: ×10
PPL and XPL

This slide can be included as an example of a peripheral pattern of weathering, although the growth of the weathered areas, as seen in appropriately oriented thin sections, seems to occur mainly along the edges of the mica. The weathering front penetrates the crystal as a series of wedges along both lateral edges of the mineral, whereas weathering seems to be much more restricted along the top and bottom edges of the stack of sheets that make up the mica. As commonly observed in such cases, the process of mesomorphic weathering, in which the primary biotite is partly replaced by chlorite, promotes the opening of lenticular pores in the unweathered part of the biotite. In PPL, the chloritized edges are pale yellow, whereas in XPL, they exhibit the commonly observed abnormal blue interference color.
**084, 085**

**KERSANTITE**
Brittany, France
Sampled in a quarry by E. Bernabe

Regular peripheral pattern of alteration around biotite

Objective: x 6.3
PPL and XPL

These two photographs are taken from a rock sample very similar to the previous one (082 and 083), but the partly weathered crystals of biotite are oriented in the plane of the thin section, so that the regular pattern of weathering can easily be recognized as a true peripheral and centripetal one. Most crystals of biotite are six-sided euhedral crystals, and their partial weathering to colorless chlorite obviously encroaches upon the primary mineral from its external margin, with formation of a regular rim whose lack of coloration contrasts strongly with the deep reddish brown color of the primary mineral. The layering of the chlorite also is parallel to the plane of the thin section; this is the reason why the rims are at extinction in XPL.

These photomicrographs show how differently the weathering patterns can appear, depending on the relative orientation of the grains in the plane of the thin section.
A particular case of a peripheral pattern of alteration is shown by the partial replacement of a crystal of nepheline by natrolite, a zeolite-group mineral. This alteration is due to a hydrothermal process according to the idealized reaction: $2NaAlSiO_4 + SiO_2 + 2H_2O = Na_2Al_2Si_2O_7 + 2H_2O$. The fluid phase preferentially penetrated the primary mineral along a direction parallel to a main axis; in the case shown here, the Z axes of both primary and secondary minerals are parallel. The contact between nepheline and natrolite is coarsely denticulate; the pattern of alteration is rather similar to that of biotite altered to chlorite (082 and 083). The upper illustration shows the very low interference-color (first-order grey) of the residual nepheline core and the low interference-color (white to first-order pale yellow) of both domains of natrolite. The second illustration, also taken in XPL but with a $\lambda/4$ auxiliary plate, demonstrates the opposite signs of the primary (uniaxial negative) and secondary (biaxial positive) minerals. The needle-shaped crystals at E5 are aegilinite, a sodium-rich clinopyroxene, whereas the smaller prismatic crystals, within both nepheline and natrolite grains, are inclusions of rinkite (= mosandrite?), $(Ca,Ce)_4Na(Na,Ca)_2 Ti(SiO_2)_5 F_2(O,F)_2$, a relatively rare mineral whose occurrence is restricted to sodium-rich alkaline rocks.
088, 089
PLAGIOCLASE-RICH AMPHIBOLITE
Koua Bocca, Côte d'Ivoire
Irregular peripheral and digitate weathering of plagioclase
Objective: x 4
PPL and XPL

Patterns of alteration illustrate the incipient weathering of plagioclase (labradorite), which exhibits its characteristic twin lamellae. The weathering starts mainly in the peripheral part of the crystal, but the centripetal advance of the weathering front is irregular and determines the formation of irregular patches and internal digitations of isotropic material. This secondary product, slightly beige-colored in PPL, shows a sharp contrast with the host plagioclase in XPL. An earlier incipient alteration of the rock, under a low-grade hydrothermal process, is responsible for the formation of microcrystals of epidote and sericite irregularly distributed through the feldspar. The surrounding hornblende has not undergone any modification, either by alteration or by weathering processes. Only some cracks, in the right part of the photograph, are enhanced by brown iron oxyhydroxides.
The weathering of an elongate subhedral grain of plagioclase starts according to two irregular patterns: the first one along the periphery of the mineral, and the second one along many transverse cracks. The combination of both irregular peripheral and linear patterns results in the isolation of many irregularly shaped residues. The secondary product is an optically isotropic material. Commonly colorless, it appears, in PPL, as pale yellowish owing to slight staining by iron-bearing solutions, whereas the median line, which runs along the linear fractures, is enhanced by a brown-colored deposit of clayey material derived from the neighboring weathered ferromagnesian minerals. In XPL, the isotropic material appears as black linear or patchy areas. No residual pores are formed around the residues of feldspar, which all have maintained their original optical orientation. The isotropic product is ephemeral and transitory; it will progressively be replaced by aggregates of gibbsite crystals. This further development of weathering will result in the gradual formation of a polyphase alteration morph. Gibbsite crystals are not yet observed in this thin section; more evolved samples, higher in the profile, must be examined to see gibbsite and a reduced proportion of feldspar residues. Incipient ferruginous weathering can be observed (B5) within a grain of clinopyroxene.
A FELDSPAR CRYSTAL of orthoclase, characterized by its simple twinning (Carlsbad law), is highly divided into numerous residual domains by a network of subparallel transverse cracks, combined with some irregular longitudinal cracks. The direction of the transverse cracks is not a reflection of a crystallographic direction of the primary mineral, but rather a result of tectonic forces acting on a thin tabular crystal. Most open spaces between the residues are filled by small crystals of gibbsite of autochthonous origin. They are directly formed from the weathering feldspar in the same way as iron oxyhydroxides are formed by the weathering of the neighboring crystals of aegirine (B5). Coatings of iron oxyhydroxides can be seen in the gibbsite-rich areas along the margin of the feldspar crystal (C4, D4). In contrast to the case shown in the previous photomicrographs (090 and 091), the feldspar weathers directly to gibbsite without passing through an ephemeral and transitory phase of optically isotropic material. The lack of such isotropic material reflects the much better conditions of internal drainage in this profile.
A moderate amount of nepheline exhibits incipient weathering to isotropic material. The microscope stage has been rotated to give the best contrast between the host mineral (first-order grey interference-color) and the secondary isotropic material (always black in XPL). The weathering process gives rise to a secondary product that is irregularly distributed (i) along the periphery of the crystal of nepheline, leading to the formation of an irregular and discontinuous peripheral area of isotropic material, and (ii) also within the host mineral, as irregular patches surrounding the intramineral inclusions of aegirine and rinkite (= mesandrite?). The first-named inclusions are greenish brown in PPL, whereas the second, smaller than the first, are pale brown. Both minerals are brightly colored (second-order interference-colors) in XPL. The left part of the photomicrograph mainly shows subparallel elongate crystals of aegirine (sodic pyroxene), whereas the right part shows a poikilitic crystal of arvedsonite (sodic amphibole). Both minerals are common in sodium-rich alkaline igneous rocks, such as nepheline syenite. Rinkite is a rare silicate mineral containing Ti, Na, F and the rare earths.
The minerals of the amphibole group are generally much less weatherable than most rock-forming minerals. Where they are the main component of the rock, as in this example, they allow the rock the opportunity to remain practically unweathered until the upper levels of the profile or to form outcrops of practically unweathered amphibolite in the upper part of the landscape. In these cases, incipient weathering is generally expressed by regular patterns of thin linear networks of iron-rich secondary minerals. These photomicrographs exhibit nearly all the possible patterns of weathering. A regular peripheral deposit of a ferruginous secondary product is clearly observed all around the largest crystals. The crystals also are crossed by transverse cracks, which are the main pathways for internal weathering of the crystals. All crystals exhibit either parallel or obliquely intersecting cleavages, which are also enhanced by thin deposits of iron oxyhydroxide. The photograph in PPL clearly shows the complex distribution of the secondary product, whereas the photograph in XPL shows that the colorless parts (in PPL) within the crystals are not residual pores, but unweathered parts of the primary minerals. These parts are not empty septo-alteromorphs formed at the expense of completely weathered grains, but rather primary crystals undergoing incipient weathering.
ANOTHER EXAMPLE of transverse fissures developed within long needle-shaped crystals of aegirine (sodic pyroxene). Most transverse fissures are oriented parallel to each other, and more or less perpendicular to the Z axis of the primary minerals. Most transverse fissures are colored by thin deposits of iron oxyhydroxides. These become thicker as the weathering of the primary mineral proceeds; the linear pattern is then replaced by a banded pattern that will isolate smaller and smaller residues of pyroxene, whose shapes will progressively change from smooth regular to finely denticulate shapes. Thicker and thicker residual pores also are developed between them (see 139 and 140). As long as the linear distribution of weathering products remains narrow, the pyroxene residues, closely fitted between the secondary products, maintain their original optical orientation. As the perinuclear pores subsequently widen, the residues will have the possibility of rotating freely, and the simultaneous extinction of the residues will be lost.
Both photographs show details of the distribution of secondary products along the periphery of the crystal and along its transverse cracks. The conditions of ferrallitic weathering prevailing in this superficial environment induce the leaching of most chemical components of the actinolite, and the fixation of its residual iron and subsidiary aluminum. This process of leaching leads to the formation of large residual voids. During incipient weathering, the residual deposit of iron oxyhydroxide is close to the mineral remnant, without appreciable pore-space between them. But with advancing weathering, the oxyhydroxide bands become progressively separated from the dissolving residues, and the iron, liberated from the actinolite, must migrate over short distances, through newly formed residual pores, to increase the thickness of the ferruginous deposit previously formed. An empty pore-volume develops between both primary and secondary minerals. The residues of actinolite acquire a denticulate shape characteristically developed on the walls of the transverse cracks, whereas the outer faces of the prism are essentially unmodified. The first opening of the cracks is still identifiable as a regular empty pore running between two parallel thin bands of ferruginous products. The development of such interconnected pore-volumes makes the rock friable, causing it to crumble to loose sand-size particles.
PATIENTS OF ALTERATION

Olivine-bearing clinopyroxenite
Koua Bocca, Côte d'Ivoire
Sampled at outcrop

Complex
(peripheral + banded)
pattern of alteration
in olivine

Objective: x 4
PPL and XPL

These photomicrographs show a complex pattern of alteration of a crystal of olivine, which at first is replaced by red-colored "iddingsite" along its periphery and along the original protoclastic fractures. Most protoclastic fractures originally contained thin lamellar deposits of magnetite (black), which have remained undisturbed during the transformation of the host mineral. They are still clearly recognizable in the banded and peripheral areas of secondary minerals. Some of these fractures have been only slightly opened at a late stage. The peripheral areas of secondary products are irregularly developed and contain small residues of unaltered olivine. The banded textures are more regular, and their thickness remains rather constant over their entire length. Several small branches of secondary products are developed in a constant orientation (C3) perpendicular to a main axis of the olivine. No residual pores are observed in this partially developed alteromorphic. Once completely developed, it will become a holo-alteromorph in which the first-developed banded textures will remain clearly recognizable within a contrasting, more homogeneous matrix. Note that at this level of alteration, the grains of clinopyroxene and poikiloblastic hornblende are not altered. These photomicrographs should be compared with the next ones, taken of a sample from the same outcrop.

102, 103

ATLAS OF MICROMORPHOLOGY OF MINERAL ALTERATION AND WEATHERING
**Part 2: Patterns of Weathering**

**Patterns of Alteration**

**104, 105**

**Olivine-bearing Clinopyroxenite**
Koua Bocca, Côte d'Ivoire
Sampled at outcrop

Complex (peripheral + banded) pattern of alteration in olivine

Objective: × 6.3
PPL and XPL

Another example of a complex pattern of alteration combines an irregular peripheral and a well-developed banded pattern. Compared to the previous illustrations, the banded textures are widened, which allows the internal organization of the associated "iddingsite" and residues of early magnetite to be more clearly recognized. As in the previous illustrations, the thin section has been rotated in such a way (45°) that both olivine and "iddingsite" exhibit their highest interference-colors; when rotated parallel to the polarizing filters (0°), both phases are optically at extinction simultaneously (not shown). The olivine residues are finely denticate in a direction perpendicular to a main axis of the primary mineral. No residual pores are observed, and the sinuosity of the dentication is common to both primary mineral and secondary product. As alteration progresses, a transitory comb texture is developed; it will disappear once the olivine residues have been completely altered. The olivine grain is then completely replaced by a holomorph in which the early-formed banded textures (with their original deposits of magnetite) will contrast with the more homogeneous matrix developed at the expense of the last-removed residues of olivine.
Peripheral and banded complex pattern of alteration in a polygenetic alteromorph after olivine

Objective: x 10
PPL and XPL

These photographs show an olivine crystal that has been partially altered to a polyphase association of serpentine and magnetite during a first step of hypogene alteration. The large residues of olivine cores have been later subjected to a second process of alteration, to brownish "iddingsite". The areas altered during the first step are minor, and restricted to straight colorless bands that follow part of the network of protoclastic fractures and part of the periphery of the olivine crystal. Deposits of secondary magnetite, genetically associated with the formation of serpentine, are locally developed (A1, C4). During the second step of alteration, parts of the olivine cores are altered to "iddingsite" that either surrounds the early-formed serpentine bands, or follows the hitherto unmodified protoclastic fractures. "Iddingsite" also penetrates the olivine crystal according to a peripheral and an irregular linear pattern. No residual pores are observed between the olivine cores and areas transformed to "iddingsite". The contact between them is expressed, in XPL, by a regular concentric distribution of the interference-colors, whose variation is due to the relative thicknesses of both phases in the thickness of the thin section. These concentric colored bands are somewhat similar, mutatis mutandis, to the contours on a topographic map.
A microphotograph of an olivine grain that is nearly completely replaced by bright red "iddingsite". The secondary products exhibit an irregular banded pattern, with the commonly observed deposits of relict magnetite. The banded texture, near the residues of olivine, is marked by an intermediate fringe of a reddish brown secondary product whose chemical composition is intermediate between "iddingsite" and nontronite (polygenetic alteramorph). Electron-microprobe analyses show that the nontronite is richer in Si and Mg than the early-formed "iddingsite". The interference-colors of the "iddingsite", in XPL, are completely masked by its intense natural color, but its transparency allows one to see that all the bands of "iddingsite", whatever their thickness or orientation, exhibit the same intensity of lighting. All have inherited their optical orientation from the original primary olivine. The banded textures, as well as the septa, which develop by the alteration or later weathering of ferromagnesian minerals like olivine, pyroxenes or amphibole, are at extinction between crossed polarizers when oriented in such a way that their constituent particles are parallel to a main axis of the primary mineral. They go to extinction simultaneously with the relict cores of the primary minerals.
The localization of the secondary products is closely related to the internal zoning of the primary mineral. In this subhedral crystal of plagioclase, the core and some of the concentric zones of the primary mineral are more calcium-rich than are the remaining parts. The zoning of the chemical composition is expressed by the concentric distribution of the secondary products: minute inclusions of muscovite – paragonite, which are responsible for the cloudy habit of some of its parts, and inclusions of epidote (high interference colors in XPL). The secondary minerals are restricted to the more calcium-rich parts of the crystal, whereas the more sodium-rich zones remain clear and free of any inclusions. Note that the distribution of the inclusions of epidote closely follows that of the micaceous secondary minerals. The alteration of the feldspar to an association of two secondary minerals results in the formation of a partially developed polyphase alteromorph according to a typical concentric intramineral pattern.
The weathering of a twinned lath-shaped crystal of plagioclase has begun along intramineral cracks, which have mainly developed parallel to the twin planes. The smectite formed as a secondary product after plagioclase has a chemical composition very similar to that of the weathering products after the neighboring minerals, such as clinopyroxene, and to that of the cryptocrystalline material formed after volcanic glass. The chemical and mineralogical homogeneity of the secondary products indicates that the weathering of the rock started in a deeply buried horizon, where transfers of elements among various primary minerals or materials occurred easily, by slow diffusion along the network of intergranular micropores.
The irregular patchy pattern of alteration appeared during the partial replacement of a subhedral crystal of quartz by secondary minerals of the zeolite group under the influence of a late hydrothermal process. Under XPL, both minerals are easily distinguished by their interference-color, pale grey for the remnants of quartz, contrasting with dark grey for the zeolite mineral. The irregularly shaped patches of secondary product are randomly distributed because quartz is a very homogeneous mineral. There are no cleavages, nor twins, nor zones to provide likely starting points for the alteration, and to influence its later development.
BASALTIC ROCK
Ocean floor,
Costa Rica Rift
Leg 70, Drill site 504b
Sampled by C. Laverne
Irregular patchy pattern of alteration in plagioclase
Objective: × 6.3
PPL and XPL

Patterns of alteration can be compared with the previous ones. The euhedral crystal of plagioclase illustrated is partially replaced by irregularly shaped and distributed patches of a zeolite-group mineral. Note that the optical orientation of nearly all patches of the zeolite is related to the orientation of the twins. In XPL, the patches of zeolite appear medium grey within the part of the plagioclase twin nearly at extinction, whereas the patches of zeolite in the medium grey member of the twin are paler. As in the previous case, the alteration of the feldspar to a zeolite is due to a hydrothermal process that occurred long after crystallization of the basaltic magma.
A microcrystalline gibbsite was first partially replaced by randomly distributed volumes of secondary natrolite of hydrothermal origin, concentrated in its peripheral and central parts. During a later step of weathering, natrolite was replaced by microcrystalline gibbsite, whereas the residual part of the nepheline was completely replaced by an isotropic secondary material. In XPL, the microcrystalline gibbsite appears as brilliant white patches that contrast sharply with the surrounding isotropic material, at complete extinction. The isotropic material exhibits an incipient reticular pattern of pores, which makes it a retiporo-alteromorph. No visible trace of the replaced nepheline and natrolite is left. This particular situation can lead to misinterpretation about the origin of the polygenetic alteromorph. Without observations on less weathered samples, one could conclude that the nepheline was first weathered to an isotropic material which, with aging, was partially converted to secondary gibbsite. A comparison with later photographs shows that the transformation of a retiporo-alteromorph of isotropic material after nepheline gives way to gibbsite microcrystals concentrated along the reticular network of pores and not to the patchy pattern shown here. The surrounding minerals are elongate crystals of aegirine and two areas of partially weathered pink eudialyte.
Illustrate another case of possible misinterpretation of the origin and the affinities of the secondary products. The upper illustration shows a large crystal of orthoclase that has been fractured and partially recrystallized, leaving irregular areas quickly infilled by a natrolite crystal (synchronous with the natrolite shown in the previous photographs). The texture suggests a case of partial alteration of the feldspar to natrolite. Orthoclase and natrolite contrast quite sharply in XPL. The first is nearly at extinction; its dark grey color contrasts with the bright white color of the natrolite. The lower illustration shows the complete weathering of the natrolite patches to microcrystalline gibbsite, leaving the host orthoclase practically unweathered. The substantial difference in weatherability between the minerals allows the natrolite to be weathered long before the orthoclase crystal. When studying a thin section similar to that shown in the lower illustration, but without knowing of the occurrence of the intermediate stage of natrolite formation, one could conclude that the gibbsite results from the direct weathering of the orthoclase. A comparison with later photographs (308 and 309, for example) shows that weathering patterns (septo-alteromorphs) involving gibbsite after feldspar-group minerals have a very different appearance.
Subject to conditions of ferrallitic weathering, a large grain of quartz in a leucocratic vein is partially weathered to an irregular patchy pattern. The dissolution-induced voids are randomly distributed within the grain, without any apparent relationship to the crystallographic orientation of the mineral. As the voids are opened by further dissolution, they are partially infilled by reddish brown clay coatings. This allochthonous material comes from the upper horizons of the soil. Some quartz particles appear as isolated remnants, but the preservation of their simultaneous extinction with the large domains of quartz shows that these remnants are interconnected, in the third dimension, by irregular bridges not visible in the plane of the thin section. As weathering proceeds, the volume of the remnants will decrease until they become free to move and able to rotate. The photograph in XPL is included to show that the colorless areas in PPL are not holes but a partly weathered colorless mineral.
THE ORIGIN Rock is a lujavite, a nepheline-bearing syenite whose main constituents are nepheline, orthoclase, aegirine (a sodic clinozoisite) and coarse-sized crystals, up to 5 cm of diameter, of eudialyte, associated with minor proportions of arfvedsonite (a sodic amphibole) and rare titanium minerals. Eudialyte is an uncommon complex trigonal silicate whose general formula is $Na_{12}Ca_{18}(Fe^{2+},Mn^{2+},Y)_7Zr_3(Si_2O_7)_4(Si_3O_10)_2(OH,Cl)_4$. In PPL, the mineral is pleochroic, colorless to pinkish. A variation in its coloration can be seen even within the same crystal. The upper photograph shows that the pink color is restricted to the parts of the mineral in contact with aegirine. The second photograph, in XPL, shows the characteristic uneven distribution of its low interference-colors; some internal parts appear to be nearly isotropic. During a first step of hydrothermal alteration, part of the eudialyte was altered, in an irregular patchy pattern, to natrolite, a secondary mineral of the zeolite group, whose higher interference-colors are clearly seen in XPL. During a later step of weathering, these same domains were partially weathered to poorly crystallized iron oxides in which part of the original zirconium content has been camouflaged. These dark brown iron-rich areas are better distinguished in PPL.
Partly Weathered Minerals

For completeness, the description of the first steps of weathering must include morphological details concerning the shape of the unweathered residues and the internal organization of the secondary minerals that surround them.

Partly weathered minerals generally occur in the lower part of the weathering profile, at or near the contact with the unweathered rock. The thickness of this intermediate level depends upon the local conditions of climate, topography, and drainage. In ferrallitic covers, this intermediate, partly weathered level can be some millimeters thick only, whereas under different conditions, and on similar parent material, its thickness can be much greater. Higher in the profile, all weatherable minerals are replaced by altermorphs of argilliplasmas or crystalliplasmas, in which all residues have disappeared. The thickness of the intermediate level also depends on the nature of the parent rock. On granitic rocks, whose constituent minerals exhibit a wider range of weatherability, the intermediate level is generally much thicker than on mafic rocks, whose constituent minerals exhibit a narrower range of weatherability.

Weighing of xenomorphic crystals of pyroxene and amphibole, which are minerals with well-expressed cleavages, commonly forms regularly shaped and parallelepiped-shaped residues that are isolated from each other by a network of open cleavages. Where weathering is more advanced, these residues more or less maintain their geometrical shapes, but detailed observation shows that the residues maintain regularly linear outlines on faces parallel to the original Z-axis of the mineral, whereas the other faces are finely denticulate.

Nevertheless, all these secondary shapes (diamond-shaped or rhomb-shaped residues) do not exactly correspond to the automorphic shape that the mineral could have in the rock if it had sufficient free space for its development during growth. These finely denticulate outlines are commonly observed, and are generally a characteristic feature of the weathering of the chain silicates (inosilicates). These denticulations also are observed at the ultramicroscopic scales.

Origin of Denticulate Remnants

Where denticulate remnants are observed in soils and in colluvial or alluvial materials, and generally in all materials that have been subjected to a transport process, it can be concluded that the remnants were extracted from a lower level of the alterite (in which this denticulate shape is common), and not from a rock outcrop subjected to erosional processes (in which fractured or irregular remnants are more common). Moreover, the distance of transport has been very short between the site of weathering and the site of deposition; otherwise, the very small and brittle denticulations would have been abraded during the transport of the mineral remnant. In contrast, detrital grains of pyroxene, for example, can exhibit denticulate shapes within soil or alluvial materials if these grains have been weathered after their transport and deposition. In this case, either an empty peripheral pore or a thick rim of secondary products surrounds the denticulate remnant, and the shape of its external boundaries is inherited from the shape of the detrital grain.
The first stage of weathering of feldspar-group minerals leaves generally irregular and cavernous residues without any particular geometrical shape. Nevertheless, the weathering of orthoclase can in some cases liberate triclinic residues (parallelepiped-shaped residues in thin section) whose shape is governed by the main cleavages of the feldspar. These well-fitted residues within the alteroplasmas can maintain their orientation and their simultaneous extinction in crossed nicols for a long period of time. The regular and geometrical shape of the residues rarely corresponds to the euhedral shape of the original grain of orthoclase.

The olivine-group minerals commonly are fragmented by irregular cracks of protoclastic origin. The shapes of the residues are rarely regular. Nevertheless, under certain circumstances of weathering to chlorite or saponite, the secondary mineral follows the pathways of these protoclastic fractures, but leaves residual fragments that are characterized by a sawtooth-shaped outline. The angles of the teeth are open, and the linear corners of the denticleation are parallel to the potential (001) faces of the olivine crystal. This coarse denticleation is reproduced parallel to itself whatever the orientation of the fracture followed by the fluids responsible for hypogene or supergene alteration. In contrast, alteration to talc, and weathering to nontronite or to iron oxyhydroxides, leave residues that exhibit a finely denticulate outline rather similar to the denticulation observed in weathered pyroxenes and amphiboles. Alteration of olivine to serpentine generally gives residues of olivine with a curved and smooth outline, at least at the scale of the optical microscope.

Where the primary minerals do not exhibit fractures or well-expressed cleavage, or a tendency to automorphs, their residues are irregularly shaped, with curved and cavernous outline, with re-entrants due to corrosion or embayments, and intramineral patches. The residues can be closely fitted within the alteroplasmas, with or without perinuclear voids. The remnants are isolated from each other by septa of argilliplasma or crystalliphasma. The euhedral shape of the mineral grain lose their unique orientation and, freely rotating in their alveolar pores, they lose their simultaneous extinction under crossed nicols.

Two more examples follow:

The first step of weathering of feldspars to gibbsite or to kaolinite, by way of an intermediate optically isotropic aluminosilicate phase, leads to numerous cavernous residues, which are isolated from each other by septa of gibbsite, by bands of kaolinite, or by irregular areas of isotropic material. Inter-plasma-mineral pore-space is not observed, and all the well-fitted residues maintain the crystallographic orientation of the primary mineral.

The first step of weathering of olivine or garnet-group minerals to iron oxyhydroxides leads to a porous and irregular structure. It consists of two components: ferruginous septa that are distributed according to the original intramineral fractures, and irregular cavernous residues. As the thickness of the ferruginous network increases and as the volume of the residues decreases, perinuclear voids develop around each residue. The thickening of the septa is achieved by intramineral nanoscale transfer of chemical elements from the core through the perinuclear pore. The residues are then loose in their cell, and their rotation promotes the loss of their common crystallographic orientation.

In summary, the residual fragments that are isolated within their alteroplasmas, with or without perinuclear pores, exhibit the following characteristic shapes, at least during part of their evolution:

- **Regular geometrical shapes**, generally ephemeral, result from the subdivision of the mineral by the opening of its cleavages and by the linear distribution of its secondary products. The remnants are numerous, regularly aligned in one or two dimensions, and exhibit a linear outline. These geometrical shapes are observed during the first step of weathering of well-cleaved minerals such as ine-, phyllo- and some tectosilicates.

- **Irregular shapes** result from the development of the regularly shaped residues into particles with finely or coarsely denticulate outlines. These shapes are mainly developed when the weathering proceeds, and the secondary plasma's structure becomes thicker. The irregular denticulation strongly obscures the previously developed geometrical outline. These shapes are commonly observed in partly weathered pyroxene and amphibole, and, in some cases, olivine.

- **Very irregular, cavernous shapes**, observed in the randomly distributed residues, result from the weathering of fractured but uncleaved, partly cleaved, or poorly cleaved minerals. The remnants vary in size and commonly show internal areas and patches of weathered material. These shapes are generally observed during the weathering of feldspars and of many other primary minerals.
Morphology of the Secondary Products

The patterns of organization and of distribution of the secondary products within partly weathered primary minerals are generally regular and homogeneous. The orientation of the elementary crystals of the argilliplasmas and crystalliplasmas is strongly influenced by the orientation of the primary mineral and, in some cases, by the orientation of transmineral fractures and intermineral suture planes. The distribution of the first-formed secondary minerals and of the associated pores is determined by the pattern of the networks of discontinuities, which were followed during this first stage of weathering. This first, early-developed distribution generally remains identifiable within the completely developed and later-formed alteromorphs.

Within the partly weathered alteromorphs, in which the mineralogically homogeneous secondary products are still associated with remnants of primary minerals, only a part of the secondary phase can exhibit a particular inherited or imposed orientation, whereas the other part is arranged according to its own regular or irregular pattern. Within the polyphase alteromorphs, which contain two or more distinct mineral phases, only one of the components, generally the first-formed one, is regularly oriented, whereas the other one is randomly oriented.

Concordance between the crystallographic orientation of the secondary minerals and that of the primary remnants is commonly observed. It is expressed either by the simultaneous extinction, under crossed nicols, of both primary and secondary minerals (as in the weathering of orthopyroxene to a smectite-group mineral, for example) or by a difference in extinction angle between the secondary and the residual minerals (as in the weathering of clinoptyroxene to a smectite, for example).

Some coincidences may be observed in the distribution and orientation of the inclusions formed within the secondary products. They result from the local concentration in the primary mineral of immobile elements that cannot enter the structure of the secondary mineral. Well-oriented needles of rutile (TiO₂) are commonly observed between layers of vermiculite formed by weathering of titanium-rich biotite.

Since some optical characteristics of the secondary minerals are in concordance with those of the primary minerals, at least partial inheritance of some crystallographic structures must necessarily be maintained during the weathering of the primary mineral, and must be transferred to the structure of the secondary mineral. This inheritance can only be maintained during the early stage of the weathering process. These first-formed crystallites are the substrate for the later products of crystallization and for their patterns of distribution. Indeed, as soon as a perinuclear void develops, the chemical elements must migrate in solution through this void to reach the first-formed secondary septa, making them thicker. The direct inheritance is then lost, but the common orientation is reconstructed at the contact with the previously formed secondary crystallites. This case is common in partly developed septo-alteromorphs after pyroxene-group minerals, in which the septa are composed of crystallites of goethite whose optical orientation is determined by the orientation of the residual fragments, from which they are separated by some tens of micrometers. In the case of the weathering of pyroxene-group minerals to goethite or to well-oriented flake of a smectite, the direction of extinction of the secondary products allows the direction of the Z axis of the primary mineral to be determined even where no remnants are still observable within the alteromorph.

The morphology of the first-developed secondary crystals can also be determined by fractures and cleavages and can exhibit regular patterns of orientation, size and crystallinity. Later generations of similar secondary products are less regularly oriented.

This is the case in saponite- or nontronite-rich alteromorphs after olivine (holo-alteromorphs), in which bands of well-formed and well-oriented crystals of saponite or nontronite follow the pre-existing protoclastic fractures. The internal volumes between these bands are entirely occupied by unoriented and microcrystalline material of similar mineralogical composition (see Fig. 8.44).

This is also the case in gibbsite-rich alteromorphs after feldspar (glomero-septo-alteromorphs). The first crystals that develop along the fractures are coarse grained, well formed and distinctly oriented relative to the fracture walls. The later-developed crystals are smaller and clustered or agglomerated following an irregular and unoriented pattern.

This is also the case in goethite-rich alteromorphs after pyroxene (glomero-septo-alteromorphs and botryo-septo-alteromorphs), in which only the central part of the septa has successfully preserved the optical orientation of the pyroxene. The lateral parts of the septa, formed by thickening of the central part, do not maintain any particular orientation inherited from the pyroxene, and occur as optically disoriented microcrystalline accumulations.
Patterns of Secondary Porosity

The orientation and crystallinity of the secondary minerals can vary from point to point within the alteromorphs. Consequently, the distribution and the morphology of the residual pores, which are associated with residual primary and neofomed secondary phases, are not homogeneous, even within monophase alteromorphs. If the weathering proceeds in a well-drained horizon, which promotes the leaching of most chemical elements of the primary mineral, the residual pore-space may become dominant. In extreme cases, only a peripheral void is developed around the remnant, or a practically empty boxwork structure results.

Microporosity and mesoporosity are distinguished according to the size of the pores connected to the secondary material. The term microporosity is restricted to the fissures, fractures and channels of higher order, which cross the alterites over longer distances.

The microstructures that are connected to the development of micro- and mesoporosities are described in more detail in a subsequent chapter, in which the micromorphology of completely developed alteromorphs is described. Nevertheless, some of the main characters that allow one to differentiate these two types of pore space are listed here.

Microporosity

Microporosity generally is an intramineral porosity (as far as original borders of the primary grains are concerned), associated with the microcrystalline structures of the argilliplasmas. The distribution of this kind of pore space is interparticular and generally uniform, especially where no inheritance of specific orientation is observed in the secondary products. This microporosity is mainly observed within the argilliplasmas, which occupy all the available space resulting from the disappearance of the primary mineral.

This microporosity, which is reduced to the empty pores existing between the microparticles of secondary products, is not easily distinguished at the scale of resolution of the optical microscope, but it can be enhanced by natural impregnation of colored materials, such as iron and manganese oxyhydroxides. Water is strongly retained within these pores, and the possible ionic transfers are slow and occur by way of diffusion-dominated processes.

Mesoporosity

Mesoporosity results from the development of secondary minerals that do not occupy all the available space created by the weathering of the primary mineral. It is commonly observed within the crystaliplasmas developed under conditions of ferrallitic weathering, in which the volume of exported elements (Na, Ca, Mg, Si) is much greater than the volumes of the imported constituents (H₂O, CO₂) combined with those corresponding to the residual elements (Fe, Al, Ti).

The shapes of the pores, their number and the regularity of their distribution depend strongly on the potential or actual microstructural properties of the primary mineral that have determined the pathways of penetration and the rate of the weathering processes. Mesoporosity is easily distinguished at the scale of the optical microscope even if the pore space is maintained empty. Mesoporosity corresponds to residual pores. Consequently, it is distributed within the alteromorphs and not at their periphery. Where distorted, opened, and connected with the other systems of pores, mesopores can be infilled by later materials of allochthonous origin.

The distribution and patterns of orientation of the mesopores provides convenient bases for further classification of the alteromorphs where all the primary residues have disappeared (see later the chapters concerning "poro"-alteromorphs).
126, 127

CARBONATITE
Jiquia, SP, Brazil
Sampled in a quarry by A.V. Walter

Thick pellicular dissolution around ankerite

Objective: x 10
PPL and XPL

These photomicrographs can be compared with those shown previously (070 - 073), taken of similar samples in the same quarry. These were chosen to illustrate the case of a thin pellicular pattern of weathering developed along intermineral fissures. Now, the dissolution of the carbonate mineral has progressed to the extent that thick pellicular dissolution-induced voids surround denticulate cores. The iron content of the ankerite, CaFe²⁺(CO₃)₂, gives way to irregular autochthonous deposits of insoluble iron oxyhydroxides, which partially infill the residual pore space. These deposits allow the original texture of the rock to be maintained on the short term, at least during the first steps of weathering. The later-developed koilooalteromorphs do not exhibit any resistance to crushing. Without the occurrence of these insoluble secondary products and of late-formed crystallaria of secondary apatite in these phosphate-rich rocks (see later, 285 and 286), they will soon disappear. Note that the shape of the denticulation of the primary mineral residues differs from that of residual pyroxene or olivine. The angle of the denticulation reflects the rhombohedral system of the carbonate; the weathering of the crystals of carbonate minerals is strongly influenced by their regular cleavages.
A biotite has been partially altered to a chlorite-group mineral. The residues of biotite are regularly distributed and oriented parallel to the cleavage of the primary mineral, whereas the chlorite exhibits a more irregular pattern of distribution. The secondary mineral forms a continuous phase, in which remnants of the primary mineral are isolated. The chlorite is pale green in PPL and exhibits its characteristic abnormal blue interference-color in XPL. The biotite is brown in both photomicrographs. The minute dark brown patches that are randomly distributed through the alteromorph are small crystallaria of titanium oxides. Titanium was a constituent of the biotite. It has been rejected by the chlorite and, consequently, it appears in a separate secondary phase. The alteromorph is polyphase. This example of an irregular banded pattern can be compared to another example (151, 152) of a very regular parallel pattern developed during a comparable process of alteration. The surrounding grains consist of plagioclase, partially altered to sericite as the biotite was being converted to chlorite.
THE PHOTOMICROGRAPHS show the beginning of the replacement of a subhedral crystal of olivine by a polyphase association of chlorite and saponite along irregular transverse fractures. The chlorite-group mineral is greenish brown in PPL, and regularly distributed along and oriented parallel to the Z axis of the crystal, whereas the yellowish beige saponite infills the areas between the thick regular bands of chlorite and the remnants of olivine. Note that the typical denticulation of the olivine appears as a "saw-tooth" pattern, which is very different from the finely denticulate pattern developed by the weathering of pyroxenes and amphiboles. Whatever the orientation of the original transverse fractures, the edges of the denticulation always exhibit the same orientations in the crystal. Note that the saponite flakes are also oriented either parallel to the edges of the denticulation or perpendicular to the Z axis of the olivine crystal. Note that the thin cracks parallel to the Z axis of the crystal have not generated a banded texture, but some of them have influenced the development of the denticulation and the distribution of its apices.
An orthopyroxene crystal (hypersthen ine) shows incipient weathering to nontronite along several irregular transverse and longitudinal cracks parallel to the cleavage. The Z axis of the crystal is more or less oriented in the plane of the thin section. Compared to the previous illustrations, note that the denticulation is much finer than in the coarse “saw-tooth” denticulation developed on the residues of olivine. This fine denticulation only develops along the banded textures more or less perpendicular to the Z axis of the crystal, whereas the edges of the residues that are parallel to this axis (and to the cleavage) do not exhibit any denticulation. This particular distribution of denticulation is invariably observed in the weathering patterns of all ferromagnesian minerals of the olivine, pyroxene and amphibole groups. In special cases (see 163), it has also been observed in feldspar-group minerals. This distribution illustrates a general rule: the apices of the denticulations are invariably oriented parallel to the Z axis for all the relevant mineral species. The thin chains of pores observed between the primary and secondary minerals are probably due to artificial shrinkage of the secondary products.
Serpentinized Komatiite
Munro Township, Ontario, Canada
Petrographic collection, Université d'Aix-Marseille III

Banded serpentine around random residues of olivine
Objective: ×10
PPL and XPL

The primary residues of olivine, whose shape and relative distribution are characteristic of komatiitic rocks (ultrabasic flows), are partially replaced by an association of serpentine and magnetite. The serpentine is distributed as sinuous banded units of regular thickness running along small residues of olivine, which show smooth and curved shapes. The serpentine, colorless in PPL, exhibits in XPL a first-order grey interference-color, which contrasts sharply with the second- and third-order interference-colors of the olivine residues. The serpentine is regularly associated with alignments of microgranular crystals of magnetite (black deposits in PPL). In the upper left corner of the lower photograph, part of the olivine crystal is replaced by talc, which exhibits high interference-colors. It is distributed in thin irregular bands, isolating many closely spaced residues of olivine. Both specific characteristics allow the area of replacement by talc to be easily distinguished from the areas of replacement by serpentine. In the lower right corner of the upper photograph, the dark brown band corresponds to an interstitial area of microcrystalline protocrystals of augite. The arrangement of olivine crystals as subparallel elongate or tabular crystals lined with areas of microcrystalline augite (and, originally, glass) is characteristic of komatiites, and is referred to as the "spinite" texture.
A network of hierarchized trans- and intramineral bands of serpentine divides a crystal of olivine into many irregular and randomly distributed residues. This first partial transformation to serpentine preceded a second phase of alteration, during which the periphery of each olivine domain was partially replaced by brownish saponite (formerly known as “bowlingite”). These two first steps of alteration belong to an early phase of hypogene origin. During a more recent episode, incipient ferrallitic weathering transformed the periphery of each residue to dark brown iron oxyhydroxides. These successive partial replacements consequently led to the formation of a polygenetic alteramorph. The last phase is also responsible for the weathering of the thin lining of magnetite within the serpentine bands. This weathering of the magnetite, together with the incipient weathering of the olivine residues, are responsible for the yellow coloration of the serpentine, which is normally colorless in PPL, and for the darkening of the saponite areas, which normally are greenish brown. The lower photograph shows that all these partial transformations, and all the secondary microtextures that they induce, affect a single crystal of olivine, as can be deduced from the uniform (blue) interference color of all the residues.
A hornblende crystal of hornblende is shown in its first stage of weathering to iron oxyhydroxides. The network of intramineral fractures is irregular and independent of the orientation of the cleavage. Several fissures cross a long, thin prism of apatite. These are intramineral fissures in the hornblende, but become transmineral (transverse) fissures in the apatite. The weathering of the hornblende begins in the upper part of the alterite. This explains why the secondary products after hornblende are exclusively brownish iron oxyhydroxides. The original iron content of the hornblende is relatively low, and as a result the secondary products do not infill all the volume available. The thin dark brown lineaments are surrounded on both sides by empty pores, whose volume is related to the amount of matter removed from the primary mineral. The amphibole residues are finely denticulate in a direction that is independent of the orientation of the fissures, but closely related to the Z axis of the mineral, and consequently parallel to its cleavage. Note that the apatite crystal does not seem to have been weathered. Its transverse fissures are coated with iron oxyhydroxides derived from the weathering of the enclosing hornblende. Some hexagonal sections of other apatite crystals are visible in the lower right corner of the photomicrograph. Some vermiculite alteromorphs after phlogopite are observed in the upper left corner, along with interstitial allochthonous infillings of organic soil material. As the degree of weathering increases, the volume of the residual hornblende will decrease, the open spaces will become wider and wider, and new fissures will probably appear. This example of incipient weathering of hornblende may be compared with a similar stage of weathering of a feldspar-group mineral (e.g., 161, 165). Although the fissure is also emphasized by a thin deposit of iron compounds, there is no residual empty pore-space, or almost none, between the fissure and the residual feldspar. Nearly all the available volume generated by the dissolution of the feldspar is filled by the secondary crystals of gibbsite. The aluminum content of the feldspar is much higher than the iron content of the hornblende; furthermore, allochthonous aluminum can be added from the weathering of neighboring grains of feldspar.
The photographs can be compared with photomicrographs 098 and 099. The samples used for the two sets of photos belong to the same weathering sequence and to the same profile. The distribution and orientation of the banded patterns are similar to those shown earlier. The bands result from the thickening of the ribbons of secondary products owing to more advanced weathering and concomitant decrease of the volume of the pyroxene residues, which take on a denticulate shape, or are even completely dissolved, leaving residual empty pores (D4). These bands are composed of two parallel alignments of crystallized iron oxyhydroxides on both sides of the median plane (central parting), which is the trace of the early-formed fissures; they can be considered as true transverse septa. At this level of the weathering profile, under conditions of strong ferralitic weathering, the associated primary orthoclase and nepheline are weathered to gibbsite (B1, E4).
141, 142

HYPERSTHENE-BEARING CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 2 m
Irregular banded pattern and random residues after hypersthene
Objective: x 6.3
PPL and XPL

The primary residues and secondary products can be compared with the previous ones; the weathering here is a little more developed, which results in the formation of thicker bands of secondary products and thinner primary residues. The distribution of the denticulation and the patterns of its orientation are similar to the previous case. Note the characteristic pinkish color of the orthopyroxene relics. Residual pores, which are irregularly distributed between the secondary and primary minerals, were artificially developed during the desiccation of the sample. All residues, well fitted within their secondary products, exhibit a parallel optical orientation, and their interference colors are homogeneous. The orientation of the secondary products is clearly observed in this alteromorph, although it was also observable in the previous photographs. Note that in the lower right corner, the pyroxene residues are directly weathered to a smectite, whereas in the upper left corner, incipient later weathering to iron oxyhydroxides is clearly distinguished. This gradual weathering will give rise to a polyphase alteromorph, whose later development is shown in photographs 377 and 378. The surrounding crystals of clinopyroxene are weathered to saponite.

PART 2: PATTERNS OF WEATHERING
B oth upper and lower photographs show the regular transverse breakage of prismatic crystals of clinopyroxene under the influence of the mesomorphic alteration of the interstitial phlogopite to vermiculite. The resulting expansion has led to the regular breakage of the prismatic crystals originally included in the mica. It is obvious that this breakage is linked to the particular orientation of the vermiculite layers, perpendicular to the prism axis of the pyroxene. Where this orientation is different, as in the upper part of the top photograph (C1 and C2), the conjugation of both orientations results in an oblique breakage of the included prisms. Such breakage allows the incipient weathering of the pyroxene fragments to a smectite. It seems obvious that if included within uncleaned poikilitic hornblende, for example, these clinopyroxene prisms would not be broken or incipiently weathered.

The lower photograph illustrates a similar distribution of both host and included minerals, but the relatively higher position of the sample in the profile leads to the development of thicker bands of smectite and denticulation of the pyroxene residues. The central part of the fractures remains empty owing to the intense breakage of the clinopyroxene into many slices separated by wide empty pores. The depth of the samples does not allow deposition of allochthonous material.
The original rock has been replaced by meso-alteromorphs of vermiculite. These have given rise to many irregular intermineral and transmineral pores, along which weathering of the clinopyroxene grains has progressed. The clinopyroxene is an iron-poor diopside, and the iron content of its secondary products (mainly saponite) is very low. The regularity of the banded texture is obscured by the simultaneous development of peripheral weathering around the crystal and around all the residues. Randomly distributed within the secondary phase, these residues exhibit the line denticulation, typically oriented parallel to the Z axis of the crystal. Several inclusions of apatite and magnetite, both primary, are included within the alteromorph. The pale beige color of the saponite is characteristic of a secondary product after such iron-poor clinopyroxene, but a slight influx of an allochthonous iron oxide is responsible for the slight darkening of the margin of the alteromorph. The photomicrograph in XPL shows the consistent orientation of the saponite throughout the alteromorph. This preferred orientation will be better explained in the next four illustrations 147, 148, 149, and 150.
The textural and mineralogical characteristics of this alteromorph after clinopyroxene are similar to those shown in previous examples. However, the primary residues are much smaller, and the main aggregate of residues (D2) is surrounded by saponite, whose usual color has been darkened by relative accumulation of iron oxyhydroxides derived from the more recent weathering of the residues (147). Photograph 148 shows the straight extinction of the secondary product, parallel to the Z axis of the clinopyroxene. The residues are not at extinction because clinopyroxene is monoclinic. Photograph 149 shows the oblique extinction of all the residues, whereas the secondary product is near its position of maximum illumination. Photograph 150 shows the simultaneous illumination of both primary and secondary minerals in a position of intermediate rotation. Note that the acute and sharp denticulation of the residues is well matched by the complementary denticulation of the secondary products.
A biotite grain has been partially replaced by chlorite. The alternation of chlorite with residues of biotite gives the alteromorph a regular parallel banded pattern. The orientations of both primary and secondary minerals also are parallel, which causes simultaneous extinction when the stage is rotated (not shown). Compared with previously shown photographs (128, 129), the interlayering of the secondary mineral within the primary mineral is much more regular, with straight contacts. The characteristic natural colors of both sheet silicates are shown in PPL, whereas in XPL, the abnormal purple-blue interference colors of the chlorite contrasts strongly with the second-order interference-colors of the biotite. Note that the thickest layers of chlorite extend through the whole width of the crystal, whereas the thinner ones are absent in its central part. Replacement of the biotite evidently started along the two opposite ends of the grain, following the cleavage. The lack of traces of radiating fissures or of late products of crystallization around the alteromorph suggests that the partial replacement of the biotite by chlorite has given rise to an isoalteromorph, and not to a mesoalteromorph.
These photomicrographs document the partial replacement of a large broken crystal of phlogopite; it is disrupted into several layers, between which regular bands of microcrystalline calcite are intercalated. The margin of the original grain is obliterated by fine-grained calcite, which has replaced most of the rock. Only remnants of mica are identifiable within a groundmass of calcite, whereas all other minerals, such as the calcic clinopyroxene, have completely disappeared. Once weathered, or upon more advanced replacement by calcite, such a kato-morphic crystal of phlogopite will become a phanto-alteromorph. Note that, up to this stage, most layers of the mica have maintained their original parallel orientation, as is clearly seen in PPL, and also in XPL, where the separated layers exhibit a nearly identical position of extinction.
A group of plagioclase is divided by a crossing network of linear fissures, which follow the two intersecting cleavages of the mineral. Secondary products are formed as the linear pattern is widened to a banded pattern. During early weathering, the primary mineral is replaced along its open cleavages by colorless or pale beige isotropic material (black areas in XPL) formed by differential leaching of the alkalis and alkaline earths, and of a part of its silica content. The highly hydrated material has a chemical composition intermediate between that of the original feldspar and that of kaolinite. The isotropic material is slightly stained by an iron compound originating from the neighboring weathered minerals.

With aging, the widest, and consequently oldest, banded isotropic parts become lined by crystallites of kaolinite, whose coloration is due to the iron stain. The grey parts observed within the feldspar residues in XPL reflect a lowering of the interference-colors owing to thinning of the residues where they are cut by the third cleavage. It lies, in this example, nearly parallel to the plane of the thin section. When complete, it will be a gradual polyphase alteromorph (see later).
Both photographs show morphological details of cavernous residues of plagioclase, first embedded within a secondary isotropic phase before the later evolution of this intermediate phase to microcrystalline gibbsite has begun. In alteration horizons subjected to processes of ferrallitic weathering, specifically in the lower parts of the toposequence, plagioclase is at least partially replaced by isotropic material. Gradually, as it loses its silica content, this isotropic phase will be replaced by gibbsite, whereas new parts of the feldspar residues will be weathered to more of the isotropic phase. The process is gradual, it develops through an ephemeral isotropic phase, and it finally gives rise to a definitive secondary material, the microcrystalline gibbsite. As weathering is not complete, it is a gradual polyphase aftermorphp. Both photographs illustrate the irregular network of the isotropic product (black areas in XPL), whose patchy or banded textural pattern is related to the cleavages and fractures of the primary mineral. Note in the lower photograph the presence of roundish isotropic patches. They are not isolated inclusions of secondary material, but rather perpendicular or oblique sections, relative to the plane of the thin section, of finger-like penetrations into the residues.
were taken a few decimeters higher than the previous sample in the same weathering profile. The photomicrographs show the progressive disappearance of the feldspar residues and the incipient crystallization of gibbsite; the thin microparticles are randomly distributed within the isotropic phase, at whose expense they are growing. The first illustration shows several cavernous residues whose size is much smaller than in the previous example, but whose shape is very similar. The elongate grains that cross the isotropic material are secondary lamellae of albite, which are not yet weathered. The innumerable very small specks that are randomly but homogeneously distributed within the isotropic phase are the gibbsite crystallites. With aging, these will progressively grow to give rise to a botryo-alteromorph.

The second illustration shows a very special case in which the primary mineral is reduced to many minute residues whose regular alignment is due to the combined effects of cleavages and twin planes. The largest unweathered grains are not residues of feldspar, but rather inclusions of primary quartz. Once the residues have completely disappeared and the gibbsite crystallites have grown, the gradual polyphase alteromorph will be converted to a botryo-alteromorph, just as in the above sample.
When subjected to conditions of strong leaching prevailing at the top of Tonkoui Mountain, which receives more than 2000 mm of rain annually, plagioclase weathers directly to gibbsite without passing through an intermediate isotropic phase. The upper illustration shows juxtaposed all the steps of weathering of a feldspar grain. In the first step (at the left), the gibbsite crystals develop on both sides of the fissures or crystal defects, producing typical septa of gibbsite. Very few residual pores are observed between the gibbsite and the residues. Gradually, as the volume of the residues decreases (in the center), more and more empty pores are developed and, where the weathering is complete (at the right), a complex but very porous glomero-septo-alteromorph results in which no more residues are observed. As long as the residues fit tightly between the septa, they maintain their original orientation; but as soon as the dissolution pores are widened, they can move freely, and lose their original orientation. The lower illustration shows the detail of a cavernous residue, completely isolated in a large dissolution-induced vugh. The dissolved aluminum removed from the residue must migrate over a short distance to allow for continued growth of the early-formed crystals of gibbsite.
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**CALC-ALKALINE GRANITE**
Blapleu, near Man, western Côte d’Ivoire
Depth: 2.2 m
Denticulate residues after orthoclase
Objective: x 10
XPL

![Image A](image1)

**164**

**BAUXITIC PROFILE DEVELOPED ON GRANITE**
Siagozohoin, Lakota, Côte d’Ivoire
Sampled by B. Boulange
Depth: 2.2 m
Quartz inclusions in a gibbsite-bearing alteromorph after feldspar
Objective: x 10
XPL

![Image B](image2)

The upper photograph shows the unusual habit of residues in a crystal of orthoclase. They are finely denticulate. The common orientation of all the residues indicates that they originate from a single grain, and that they are not free to move. They are completely embedded in an isotropic secondary product that maintains them in their original orientation and spatial distribution. The intermineral fissures that surround the alteromorph after orthoclase and the transverse fractures that divide them have given rise to a rim and to irregular septa of well-crystallized gibbsite. The isotropic material is not yet replaced by gibbsite crystals (or if so, to a very limited extent); these will take on a glomero-alteromorphic pattern in each inter-septum area. Note that the quartz grains (C5) are not weathered. Quartz also appears with sodic plagioclase in a myrmekitic intergrowth (A3). It has preserved its characteristic shape and distribution, whereas the associated sodic plagioclase has completely weathered to the isotropic phase.

The lower photograph shows inclusions of quartz (unweathered) within a gibbsite-bearing alteromorph after feldspar. The intermineral fissures around the inclusions have served as pathways along which the weathering of the feldspar began.
Both photomicrographs show a combination of an irregular pattern of incipient weathering, which is related to irregular transmineral fractures, and a regular pattern of distribution of the secondary gibbsite, which is related either to the presence of polysynthetic twinning in plagioclase (165) or to the poorly developed cleavages of orthoclase (166). In both cases, the median plane of the septa is emphasized by brown-colored iron oxyhydroxide deposits, mainly in the widest septa, which are related to irregular fractures. Note that the formation of septa, which are regularly distributed within the larger residues, is soon replaced, in the completely weathered parts, by the development of a more complicated texture in which the early-formed septomorphic pattern is associated with a glomeromorphic pattern (along the right edge of both photographs). Before disappearing, the feldspar residues take on an irregular cavernous habit; shapes are independent of the presence of twinning and a network of cleavages.
This photomicrograph shows the distribution and details of the shape of the residues acquired after initial ferralitic weathering of plagioclase. Fractures and fissures cross the primary mineral in (i) an irregular pattern, giving rise to large irregular bands of isotropic material, and (ii) a network parallel to the twin domains, as is clearly seen to the right. Within the large areas of isotropic material, microcrystals of gibbsite are randomly distributed, without any particular orientation or concentration. On the other hand, along the twin planes, the microcrystals of gibbsite exhibit a regular arrangement typical of septo-alteromorphs, in which they are invariably oriented perpendicular to the trace of the fissures, whose orientation is strongly influenced by the twin planes of the precursor. All residues of feldspar show an irregular outline and a cavernous shape, as is typical in such weathered material. Some residues exhibit holes or irregular internal black patches. These holes and patches are probably not isolated features within the host mineral, but perpendicular or oblique cuts of digitations and embayments. Traces of the twin planes are visible within some residues.
Part 3

Alteromorphs
A nanobedral crystal of olivine has been altered, by a late magmatic process, to a holo'-iso-alteromorph of "ildingsite". The alteromorph is characterized by the abundance of the secondary product, which completely fills (holo-) the volume available without forming intraminal pores. At the same time, the original shape and volume (iso-) of the original grain of olivine are maintained. Most cracks in the alteromorph are traces of protodastic fractures that are still coated with minute grains of magnetite, likely of early postmagmatic origin. The variability of the red color in several sectors is due to impregnation of black Mn-oxide along a transmineral fracture. For further explanations, see photomicrographs 265 and 266.
CHAPTER 6
Definitions

Definitions

Introduced classifications (Stoops et al. 1979, Bullock et al. 1985) are satisfactory for the description and classification of the micromorphological patterns observed within partly developed alteromorphs (classes of alteration 1, 2 and 3), but these classifications are imprecise when it comes to patterns that occur within completely altered minerals (class of alteration 4). In order to fill this gap, a new classification has recently been proposed (Delville 1994).

The terms pseudomorphosis and pseudomorphism are commonly used to describe the process by which a primary mineral, identified by its specific shape, is replaced by a secondary mineral (or by an aggregate of secondary minerals) with retention of the shape and volume of the primary one, whatever the mineralogical and chemical compositions of both primary and secondary constituents. The result of the replacement, as it appears in thin section, is a pseudomorph. According to the etymology of the term (from the Greek θείως wrong, false, that which is not what it seems to be, and μορφή = shape), and according to the above definitions, the terms pseudomorphosis, pseudomorphism and pseudomorph should be used only in the case of the replacement of an automorphic (from the Greek ευτος = own, particular, from itself) or euhedral (from the Greek ευ = well and ὑπάρχω = base, face) primary mineral, characterized by well-developed crystallographically indexable faces, by secondary minerals, with preservation of the shape and characteristic outline of the automorphic (euhedral) primary mineral.

Most rock-forming minerals have poorly developed faces, and their shapes are uneven and not diagnostic; they are xenomorphic (anhedral) minerals (from the Greek ξενός foreign and οὐ = without). In most cases, the use of the term pseudomorph is thus improper to describe the secondary products and textures derived from xenomorphic primary minerals which, by definition, do not exhibit a characteristic shape or well-developed faces.

Although the term pseudomorph is commonly used by most mineralogists and petrographers to describe, from a geometrical standpoint, the entities derived from the replacement of a primary mineral by secondary minerals, with preservation of original outline of the mineral considered, regardless of its shape, a new term is proposed to designate such an entity:

The general term alteromorph (from the Latin alter = other, and from the Greek μορφή = shape) will be used in all cases of transformation (alteration or weathering) of primary minerals to secondary products, whatever the shapes of both primary and secondary minerals and whatever the extent of preservation of their original shapes and volumes.

This definition does not concern bodies that result from the infilling of pre-existing or synchronously developed pores, such as open transmineral fractures, vesicles in effusive rocks, and all pores of pedological or biological origin. These entities are situated outside the alteromorphs, from which they are genetically independent. The alteromorph's structure corresponds to the min-phane-seplic fabric: a completely weathered primary mineral is present in the plasma as a distinct entity (Bisdom 1967b).

The term alteromorph is of general utility, and not only applicable to the case of near-surface weathering of minerals. It also applies to the case of replacement of a mineral by hypogene metamorphic or hydrothermal processes. In theory, the use of this term should be restricted to the case of completely altered or weathered minerals in which no primary remnants are observable. If the process of alteration or weathering is not complete, the terms partly developed alteromorph and partial alteromorph are more adequate, and the nomenclature discussed in the previous chapters is applied.

The illustrations in this chapter include many photomicrographs of partly developed alteromorphs. They are much more interesting than completely developed alteromorphs because they give more information
about the pathways by which these alteromorphs developed, and about the nature of the primary mineral from which they are inherited. The esthetic, contrasted and didactic impact of these photomicrographs is much enhanced by the fact that they show primary and secondary minerals together. The reader can more easily imagine both the initial state and final result of the alteration or weathering process, and the progressive development of the alteromorphs.
A 'thal develops by the complete weathering of a primary mineral does not always exactly preserve the shape, size and volume of the mineral that it has replaced. Depending on the extent of preservation of the original structures and volumes, the terms isomorphous, mesomorphous and katamorphous alterations were proposed (Stoops et al. 1979). By using the same etymological roots and by maintaining the content of the previous definitions of these authors, three new terms, based on a geometrical concept, have been proposed (Delvigne 1994); these are iso-, meso- and kataalteromorph (Figs. 11–14).

Figure 11. Definitions of alteromorphs on the basis of geometrical criteria, i.e., extent of preservation of volumes, shapes and boundaries.
Unequal modifications in one or two dimensions may introduce perceptible and measurable deformation of the secondary texture. This kind of alteromorph also is common in isalterites, but it commonly corresponds to the weathering of specific groups of minerals, such as the phyllosilicates (sheet silicates).

The weathering of biotite to vermiculite or kaolinite is accompanied by an important expansion of the original volume perpendicular to the layers of the mica, whereas the other dimensions remain practically unmodified.

The development of meso-alteromorphs, especially where they are abundant in a weathered rock, rapidly leads to the fracturing or dislocation of surrounding or included minerals. Some meso-alteromorphs may form only if the primary mineral is entirely isolated within a large pore, which allows its full development. The weathering of crystals of vermiculite into mesomorphous (or in some cases, katamorphous) kaolinite occurs only where the flakes of vermiculite are subjected to strong leaching once they are isolated within large interconnected pores or chambers. The original rectangular shape of the vermiculite flakes becomes rounded, swollen and undulating, with a final shape similar to popcorn (pop-alteromorph?) (see below, photomicrographs 193–196).

**Kata-alteromorphs**

The term kata-alteromorph (from the Greek κάτα = downward) is used where important modifications of the shape and volume have occurred in the three dimensions. Outlines are no longer clear or continuous, but the position of the original mineral is still recognizable (Fig. 14).

Kata-alteromorphs are common in alloterites, and their importance increases up the weathering profile. The distortion of the alteromorphs during their
development is commonly influenced either by swelling and shrinkage in expandable secondary minerals, or by external processes such as fracturing, dislocation, and dissemination of brittle or breakable secondary minerals, or by degradation and assimilation of the secondary products during later processes of pedoplasmaton* or pedoturbation*. All iso- and meso-alteromorphs can later be converted into kata-alteromorphs either by chemical degradation and alteration of their argilliplasmas, or by physical deformation of their content of cleaved and easily deformable clay minerals. Whereas the development of most meso-alteromorphs seems to be responsible for the deformation of the surrounding minerals, the development of a kata-alteromorph, in contrast, is more commonly the result of disturbance or destruction due to physical or chemical factors external to and independent of the alteromorph considered.
MINERAL PATTERNS

PHLOGOPITE-RICH CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 2.6 m
Meso-alteromorph after phlogopite
Objective: × 6.3
PPL

PHLOGOPITE-RICH CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 0.8 m
Meso-alteromorph after phlogopite
Objective: × 6.3
PPL

The lower photomicrograph illustrates the extent of deformation resulting from the alteration of a phlogopite crystal to a vermiculite meso-alteromorph. The increase in volume is only perceptible in a direction perpendicular to the layering of the mineral. The basal section of the apatite inclusion allows one easily to visualize the direction and the extent of volume increase. By measuring the actual diameter of both inclusion and surrounding pore, the percentage of the volume increase in this case can be estimated to have been 50%.
The previous example showed the case of an apatite inclusion lying parallel to the plane of the layers of the host vermiculite. Formation of a peripheral pore occurred as a result of expansion in isolation from the matrix. The present case shows what happens when a prism of apatite is nearly perpendicular, or slightly oblique, to these planes. Owing to the expansion of the host mineral (now vermiculite) in a direction perpendicular to its layers, the inclusion, which cannot be compressed nor curved, is fragmented; numerous transverse fractures divide it into a series of juxtaposed slices. Their relative displacement allows one to visualize the orientation and extent of the expansion. Note that prisms of diopside (C2, A4, B5), which are parallel to the apatite inclusion and in a comparable situation, also are broken up by several transverse fractures, along which the clinopyroxene fragments have partially weathered to saponite.
A biotite-rich clinopyroxenite, whose layers are nearly perpendicular to the plane of the thin section, is transformed into a meso-alteromorph characterized by the occurrence of many lenticular intramineral pores. The weathering proceeded in two steps. After having lost most of its interlayer potassium, the layers of octahedra in the structure lost iron, which precipitated as minute particles of oxyhydroxide within the cleavage of the mica. These brown-colored centers of crystallization protected the layers from further expansion, and considerably diminished the accessibility of the central part to the agent of weathering. These iron-rich parts cannot easily be expanded without further release of the cementing iron oxyhydroxides. In the peripheral parts of the crystal, where the exchanges are easier, the iron compounds were lost, and the layer silicate was more easily expanded and transformed to colorless kaolinite. This transformation is made with considerable increase in volume in a direction perpendicular to the layers. Consequently, kaolinite wedges developed along the margin of the meso-alteromorph promote the separation of the central part and the opening of lenticular intramineral pores. The meso-alteromorph (according to geometrical criteria) has become a phylloporo-alteromorph (according to internal microtextural criteria).
174, 175

BIOTITE-RICH
CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 4.8 m
Meso-alteromorph
after biotite
Objective: × 10
PPL and XPL

This is an extreme case in the
formation of lenticular
intramural pores as a result of the
transformation of biotite to a
kaolinite meso-alteromorph. The
strongly indurated central part of
the oxidized mica cannot expand in
response to the stresses developed
in the kaolinite-rich domains at the
margin. Considering that the layering
of the primary mica is nearly
perpendicular to the plane of the
thin section, the expansion accom-
panying the formation of the meso-
alteromorph can be estimated by
comparing the total thickness of the
alteromorph to the sum of the
thicknesses of each iron-oxide-
curiched layer (the measurements
are restricted to the rectangular
part of the alteromorph included in
BCD and from 1 to 4). Such mea-
urements give an approximate
expansion-ratio of 250%. This
meso-alteromorph thus exhibits in
its central part a pore volume
largely exceeding the volume of the
residual material. Its internal
microtexture can be compared to a
ladder whose sidepieces are the
kaolinite-rich parts, and whose
rungs are the layers of residual
biotite ("ladder-shaped" meso-
alteromorph).
When mechanical processes transform a biotite crystal to chlorite, the expansion provoked by the mesomorphic character of the transformation can open lenticular pores, which become infilled by allochthonous materials transferred from other parts of the rock by hydrothermal fluids. In the case shown here, lenticular pores are infilled either by calcite or quartz. The two secondary minerals are not easily distinguished in PPL, but the difference in interference-colors in XPL allows these minerals to be easily distinguished. Pale green chlorite has developed either on both sides of the biotite crystal or according to irregular pathways through its central part. The original titanium content of the biotite, which does not enter the structure of the chlorite, is expressed as minute individual crystals of titanite (dark brown grains randomly distributed within the chloritized biotite, as at B1 and D3).
Granitic Rock
Siogofoho, Lakota,
Côte d’Ivoire
Sampled by B. Boulangé
Depth: 1.8 m
Meso-alteromorph
after biotite

Objective: x 6.3
PPL and XPL

Where subjected to conditions of ferrallitic weathering, crystals of biotite are generally transformed to polyphase meso-alteromorphs of kaolinite and iron oxyhydroxides. Thick layers of kaolinite are regularly distributed and interstratified between more iron-rich layers, which hold the iron content of the primary mineral. Lenticular intramineral pores also may develop. They may be infilled either by kaolinite of allochthonous origin, or by crystalliplasmas of allochthonous gibbsite. The appearance of gibbsite generally is concomitant with the destruction of the previously formed kaolinite and with its replacement by crystalliplasmas of gibbsite of autochthonous origin. The photomicrographs show a meso-alteromorph after its final stage of weathering. The red-colored layers of iron oxyhydroxides are regularly associated with lenticular or planar intramineral areas, which represent the final stage of desilication of the kaolinite to form a gibbsite-rich crystalliplasma. The occurrence of allochthonous gibbsite is confirmed by the fact that crystalliplasmas also appear within the irregularly distributed round pores and within all the extramineral pores, in some cases associated with infillings of dark brown ferruginous products.
The upper photomicrograph shows a small crystal of biotite that has been completely weathered to a booklet of kaolinite. Most of the original iron content has been leached out, but the surrounding iron-enriched intermineral fissure has provoked this differential behavior in the margin relative to the internal area. The iron-enriched parts have not expanded to the same extent as the central part, which results in this unusual habit of the meso-alteromorph.

The lower photomicrograph illustrates the behavior of a coarse crystal of kaolinite after vermiculite in response to stresses within the superficial soil horizons. The brittle and malleable meso-alteromorph is strongly deformed, it gets a curved habit, and many of its segments are relatively displaced along intramineral joint-planes. Although this alteromorph displays, in three dimensions, a shape that differs significantly from its original shape, it seems that the term meso-alteromorph is more appropriate than the term kata-alteromorph, which pertains to more complex and divided shapes (compare, for example, these photographs with 197 and 198, taken in the same profile).
The rock originally consisted of phlogopite-rich clinopyroxenite. Its phlogopite crystals were altered to vermiculite during an early step of hypogene alteration. During a later step of weathering, in the lower part of the deep profile, the clinopyroxene grains were weathered to phyllophoro-alteromorphs of a smectite-group mineral, whereas the vermiculite did not undergo any later transformation. Higher in the profile, under conditions of strong leaching during a previous episode of ferrallitic weathering, the smectite component of the alterite was transformed to many small crystals of kaolinite irregularly associated with dark red concentrations of residual hematite (black patches and lineaments in PPL), whereas the vermiculite meso-alteromorphs were weathered to a second generation of meso-alteromorphs of kaolinite. The increase of volume during this second transformation is added to the earlier increase due to the transformation of phlogopite to vermiculite, and is expressed by the long, curved and faulted crystal of kaolinite.
Restricted drainage prevailing in the lower part of a profile developed on a biotite-bearing granite, the flakes of biotite are weathered to a smectite. The replacement generally starts along the periphery of the flakes, and extends irregularly toward the center of the mineral. Irregular intercalations of secondary products progressively separate the primary biotitic into many flakes of variable thickness. The secondary product is a swelling clay, which results in the irregular expansion of the primary mineral and in the progressive destruction of its original shape. The result is a meso-alteromorph, which is turned into a kata-alteromorph progressively as weathering develops. The large increase in volume of the kata-alteromorphs, compared to the original volume of the primary grains, promotes the opening of many trans- and intermineral fractures in the neighboring feldspars and a large increase in the likelihood that they will weather. Most of the biotite in the deformed basement granite is regularly distributed and interlayered with leucocratic layers of quartz and feldspar minerals. The preferential weathering and swelling of these mica-rich layers thus cause the opening of the regular foliation of the rock over a thickness of several meters.
The pattern of weathering of mica shown in these photomicrographs is rather similar to the one previously illustrated. The biotite has weathered to a smectitic clay but, in this case, the weathering is complete, and no residual biotite remains in the meso-kata-alteromorphs. The buildup of pressure due to the swelling of the clay promoted the deformation of all the partially developed alteromorphs after biotite into small elliptical meso-alteromorphs, each of them resulting from the individual swelling and relative movement of separated parts of the primary grain. The deformation of the meso-alteromorphs is expressed by irregular alignments of elliptical domains, which may have developed from a single crystal of biotite. The internal movements of sliding and faulting also promote the breaking away of very fine particles of smectite, which are soon displaced and concentrated as infilling material within the neighboring open fractures and pores. The uniform optical orientation of the particles still observable within the meso-alteromorphs is lost when the particles are individually displaced. This infilling material is then associated with small skeleton grains of less weatherable minerals, such as quartz and feldspar.
A sample of mica-rich clinopyroxenite, in which the biotite-rich zones alternate with pyroxene-rich areas, is partially weathered. The biotite has been weathered to kaolinite after an intermediate stage of alteration to vermiculite. Both processes are responsible for the strong deformation of the sizes and shapes of the mica, and for the consequent development of kata-alteromorphs. The other rock-forming minerals are fractured, relatively displaced, and partially weathered to a smectitic product. The opening of large trans- and intermineral fractures allows cutans of subautochthonous smectite to be deposited. The volume increase of many aligned adjacent alteromorphs induces the development of irregular, curved and distorted bands of secondary kaolinite, whose orientation is related to the oriented texture of the original rock. The distortion of the kata-alteromorphs occurs in the three dimensions, as can be deduced from the fact that the kaolinite layers, even in a given alteromorph, are not always perpendicular, but are often progressively oblique and then parallel to the plane of the thin section. This can be deduced from their interference-colors and by the progressive inclination of their optic axes in XPL (not shown), and especially from the regular variations in the quantity of greyish black microparticles interlayered within the booklets of kaolinite. These microparticles mainly consist of titanium oxide. Titanium, derived from the primary titanium-rich biotite, does not enter the structure of vermiculite, nor that of kaolinite. It precipitates as insoluble particles distributed between the layers of the secondary sheet silicate.
During a first step of late magmatic alteration, several grains of olivine were completely transformed to "iddingsite" iso-alteromorphs, whereas the phlogopite present in the rock was altered to vermiculite meso-alteromorphs. During a later step of supergene weathering, the "iddingsite" was replaced by goethite. Magnesium and silica were lost, but the original orientation of the "iddingsite" was maintained. The clinopyroxene was first weathered to saponite and later to kaolinite, whereas the vermiculite also was weathered to kaolinite. The internal movements in the altered and then weathered rock, due to strong expansion of the secondary products during their formation, provoked the breakage of the brittle grains of "iddingsite" and the subsequent deformation and breakage of the iso-alteromorphs into kata-alteromorphs. Under XPL, the different colorations of the "iddingsite" areas indicate that their optical orientations have been directly inherited from several randomly oriented grains of olivine. The relative movement of the fragments of the broken alteromorphs led to the somewhat heterogeneous coloration of each alteromorph. The small black areas (XPL), mainly visible within the "iddingsite" areas, correspond to interstitial pores derived from the breakage of the alteromorphs.
The photomicrographs show the recent weathering of a building stone subjected to rain and to atmospheric pollutants. A thick weathered cortex progressively became separated from the fresh building stone by a progressively thicker and thicker irregular fissure as the weathering extended toward the center of the building stone. Exfoliation of a biotite crystal resulted in a typical kata-alteromorph under the influence of many minute crystals of gypsum growing between the layers of the mica. The gypsum clearly shows up in XPL as minute diamond-shaped crystals with low interference-colors (first-order grey). The minute black spots, which are widespread along the margin of the alteromorph, are minute residues of organic material (fungi, lichens, etc.). These residues are associated with small particles of secondary calcite. The large empty pore, which lies along the lower edge of the photomicrograph, corresponds to the opened fissure formed between the weathering crust and the hard building stone, under the combined influences of rain and atmospheric pollutants. The part of the biotite crystal that is not exfoliated shows several irregular inclusions of titanite.
During the step of hypogene alteration, the phlogopite in the rock has been altered to vermiculite, which resulted in the formation of many meso-alteromorphs and promoted the disruption of the primary rock. When subjected to superficial processes, under the influence of pedoturbation, many residual minerals have been mixed into the reddish brown pedoplasma. The vermiculite residues are quickly transformed into Kata-alteromorphs of kaolinite under the influence of conditions of extreme leaching that prevail in the highly fissured and fractured superficial horizons. Where the vermiculite grains fit tightly within the soil material, little damage occurs, but where they protrude within the network of pores in the soil, they expand irregularly and form Kata-alteromorphs composed of kaolinite, whose volume and shapes differ significantly ("pop-alteromorph") from the original volumes and shapes of the primary mineral. In the beginning stage of weathering, the vermiculite is irregularly weathered, and many thin and distorted layers of unweathered vermiculite are still distinguishable within the colorless kaolinite component of the kata-alteromorph.
The upper photomicrograph illustrates the case of a small residue of vermiculite. Part of it, fitting tightly within the soil material, is not yet weathered. The other part, protruding within a large empty pore, is completely weathered to colorless kaolinite. The kaolinite portion of the alteromorph has acquired a roundish fan-like shape under the influence of the expansion that prevailed during the mesomorphic weathering of the vermiculite.

Once completely released from the surrounding matrix, all the residues of vermiculite weather to roundish kata-("pop")-alteromorphs of colorless kaolinite which, under the influence of further pedoturbation, can be again mixed within the surrounding matrix, as are the other residual primary or secondary minerals, giving rise to the unusual distribution shown in the lower photomicrograph. The pale yellow color of the pore areas is due to artificial staining of the impregnating material during the making of the thin section. This allows the colorless kaolinite-rich kata-alteromorphs to be easily distinguished.
**Soil developed on biotite-rich granite**

Akuvikro, Dimbokro, central Côte d’Ivoire

Depth: 3.6 m

Meso- and kata-alteromorphs after vermiculite

Objective: × 6.3

PPL

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**Soil developed on biotite-rich granite**

Akuvikro, Dimbokro, central Côte d’Ivoire

Depth: 4.8 m

Meso- and kata-alteromorphs after vermiculite

Objective: × 10

PPL

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The upper photomicrograph shows an irregular assemblage of many meso- and kata-alteromorphs resulting from the weathering of biotite crystals to kaolinite after an intermediate step of vermiculite. All these chemically resistant alteromorphs are now mixed within the soil material, but their poor mechanical resistance is responsible for their deformation. The irregular distribution of all these alteromorphs, and the difficulty to recognize the original shapes and outlines of each alteromorph, make them comparable to a cryptomorphic assemblage of alteromorphs (see later). Alteromorphs are deformed owing to the internal pressure generated by soil movements; many of them are microfaulted and distorted by internal faults and microglides.

The lower photomicrograph shows, in its central part, a kata-alteromorph after biotite — vermiculite that has become fragmented and distorted, in the three dimensions, into many pieces whose shapes and orientations allow the position and the nature of the primary mineral to be easily recognized. These micromorphological characteristics satisfy the definition of a kata-alteromorph.
Four more particular cases of alteromorphs are common. Their patterns are closely related to the first level of classification, based on the extent of preservation of the shapes and sizes during the weathering process. These characteristic modifications are included in the definitions of the four following terms.

**Pseudomorphs**

The term pseudomorph (from the Greek ψευδός = error) refers to a particular case of an alteromorph: it results from the isomorphous weathering of a euhedral mineral, which maintains its well-developed and characteristic faces (Fig. 15). The term “pseudo-alteromorph” cannot be used, because it conjures up a contrary meaning.

Euhedral minerals are not very widespread in common rocks. Consequently, pseudomorphic alteromorphs are not commonly observed in their alterites. Among the common euhedral primary minerals are some accessory minerals such as zircon, apatite, titanite, magnetite, pyrite, garnet, staurolite and epidote. The quartz of hydrothermal veins in some cases exhibits a euhedral outline. Many of these minerals are not easily weathered, and they can persist for a long time in the weathered layers and soils. Euhedral phenocrysts of olivine, augite, plagioclase and leucite also are observed in effusive rocks, and euhedral crystals of pyroxene, amphibole, garnet and epidote are common in intrusive or metamorphic rocks. These more weatherable minerals commonly produce pseudomorphs, whatever the conditions under which they are weathered.

Natural crystals are not always perfectly developed. Thus the definition of pseudomorph can be extended to alteromorphs derived from well-developed crystals whose outlines exhibit some defects, embayments, inclusions and irregularities, such as are found in subhedral and skeleton crystals.

The characteristic shape and crystal faces of the primary mineral are perfectly maintained regardless of the crystallographic systems of the secondary minerals. Examples include: a euhedral bipyramidal prism of olivine (orthorhombic symmetry) replaced by an aggregate of flakes of a smectite-group mineral (phyllosilicate with a monoclinic symmetry), a euhedral monoclinic crystal of augite replaced by an aggregate of goethite microcrystals (orthorhombic symmetry), a euhedral crystal of plagioclase (triclinic) replaced by an aggregate of small crystals of gibbsite (monoclinic symmetry), a cubic crystal of pyrite replaced by an aggregate of hematite crystals (hexagonal symmetry). All these alteromorphs maintain the shape and volume of the original minerals; the shape typical for the symmetry of the primary mineral is preserved regardless of the symmetry of the secondary mineral. This preservation of the characteristic shape justifies the term pseudomorph. The secondary mineral, or the aggregate of secondary minerals, has inherited a characteristic shape that is not its own.

**Echino-alteromorphs**

The term echino-alteromorph (from the Greek εχείνος = urchin) refers to a particular and uncommon case of the mesomorphic pattern, from which it is distinguished by the fact that a part of the secondary material, mainly a smectitic clay, protrudes beyond the outline of the original mineral by infilling radiating intermineral* or transmineral* fractures opened around the primary mineral by the internal pressure of the expandable plasmas of the alteromorph (Fig. 16).

The general shape of the primary mineral is relatively well preserved, because only radiating “spines” of alteroplasma are added to the slightly modified outline. The infilling material of these open radiating fractures is generally the same as that within the alteromorph. Infillings of nontronitic or saponitic clay expelled...
beyond the border of an alteromorph after olivine or pyroxene are common in radiating intermineral fractures opened among adjacent grains all around the smectite-rich alteromorph.

In alteromorphs that develop under the influence of hypogene processes, the secondary products may consist of two different mineral species. In this case, the main constituent generally occupies mostly of the alteromorph, inside the original boundaries, whereas the minor (or the most mobile) constituent is concentrated peripherally and in the newly formed volumes developed in the radiating fractures. For example, the hydrothermal alteration of orthopyroxene may give rise to talc associated with minute particles of magnetite, which concentrate the iron that has not been incorporated in the relatively magnesian talc. Talc forms most of the alteromorph inside the original boundaries, whereas magnetite grains are preferentially concentrated in a rim and as infillings of the radiating fractures. The serpentinization of isolated grains of olivine in an olivine-bearing pyroxenite provides another example of echino-alteromorphs. Serpentine-group minerals occupy the innermost part of the alteromorph, whereas the associated magnetite is preferentially concentrated in a peripheral rim and as infillings of radiating fractures (see below, Fig. 37A).

Another example of an echinomorph is given by the metamorphic or hydrothermal alteration of pyroxene to amphibole. A monomineralic grain of pyroxene is replaced by a radiating aggregate of amphibole needles and prisms (cummingtonite, tremolite, actinolite). These secondary minerals have a tendency to show pronounced automorphic development; they may continue to grow outside the original outline, and they penetrate into the secondary products formed at the expense of adjacent minerals. If the adjacent minerals are also grains of pyroxene, their transformation results in similar patterns, and contiguous echinomorphs are formed whose radiating needles and prisms are strongly interconnected and intricate (see below, Fig. 37B). The original outline of the grain is in some cases identifiable owing to thin deposits of magnetite, regularly distributed along these outlines. Where these outlines are no longer identifiable, the aggregate of echino-alteromorphs may become an aggregate of crypto-(echino)-alteromorphs (see below).

The term phanto-alteromorph (from the Greek ϕάντασμα = phantom, ghost) refers to a particular case of a katamorphic pattern of weathering in which minute residues or traces of secondary products or textures, with irregular, discontinuous or diffuse outlines, are observed within a matrix with which they contrast by their color, density, crystallinity, shape or internal texture (Fig. 17). Phanto-alteromorphs are commonly observed in partially replaced materials. The original margins are no longer recognizable because they are progressively obliterated and assimilated by the surrounding matrix. The position of the primary mineral is generally identifiable; it is seg-

![Phanto-alteromorph](image)

**Figure 17.** Relationship of a phanto-alteromorph to a grain of a primary mineral.

Phanto-alteromorphs are commonly observed in partially replaced materials. The original margins are no longer recognizable because they are progressively obliterated and assimilated by the surrounding matrix. The position of the primary mineral is generally identifiable; it is seg-

![Phanto-alteromorph](image)

**Figure 17.** Relationship of a phanto-alteromorph to a grain of a primary mineral.

Another example of an echinomorph is given by the metamorphic or hydrothermal alteration of pyroxene to amphibole. A monomineralic grain of pyroxene is replaced by a radiating aggregate of amphibole needles and prisms (cummingtonite, tremolite, actinolite). These secondary minerals have a tendency to show pronounced automorphic development; they may continue to grow outside the original outline, and they penetrate into the secondary products formed at the expense of adjacent minerals. If the adjacent minerals are also grains of pyroxene, their transformation results in similar patterns, and contiguous echinomorphs are formed whose radiating needles and prisms are strongly interconnected and intricate (see below, Fig. 37B). The original outline of the grain is in some cases identifiable owing to thin deposits of magnetite, regularly distributed along these outlines. Where these outlines are no longer identifiable, the aggregate of echino-alteromorphs may become an aggregate of crypto-(echino)-alteromorphs (see below).

Thread-shaped or foliated relics after micas and septa structures after feldspar, completely embedded in a hematite- or gibbsite-rich matrix, are common in old iron crusts and bauxite. These are good examples of phanto-alteromorphs in which the epigenetic process involving iron and aluminum has progressively modified the shape and internal texture of the previously formed alteromorphs. The residues are shapeless, and their primary origin is identified only with difficulty. They seem slightly different from the surrounding matrix only by a perceptible modification of their color, of the degree of their crystallinity, or by a difference of optical orientation. Such phanto-alteromorphs occur within calcrites and silcretes, and, in general, within all layers and horizons where an epigenetic process involving elements such as Fe, Al, Ca, and
A genetic process involving elements such as Fe, Al, Ca, and Si plays a dominant role.

**Crypto-alteromorphs**

Crypto-alteromorphs (from the Greek κρυπτός = to hide, to mask, to conceal) result from an assemblage of adjacent alteromorphs, generally iso-alteromorphs, whose individual original boundaries, although maintained, are no longer clearly identified under the microscope. All adjacent crypto-alteromorphs exhibit similar mineralogical and microtextural contents (Fig. 18).

Where several adjacent grains of a specific mineral are completely weathered to similar aggregates of secondary products, it is common for the products not to exhibit any particular characteristic or specific orientation. Although the replacement has occurred without modification of size and shape (to give, for example, a group of iso-alteromorphs), the boundary of each original grain is no longer identifiable because all the alteromorphs exhibit a similar composition and a similar internal texture. Several different outlines can be suspected, supposed or imagined for each of them.

This case is common in monomineralic and in some glomero-alteromorph rocks. Most of their constituent minerals are weathered to similar secondary minerals, which exhibit similar textures. It is also observed where different associated primary minerals are all weathered to the same secondary products.

Both olivine and pyroxene, in a basic rock, may be replaced by crypto-alteromorphs of iron oxyhydroxides: orthoclase, plagioclase and nepheline in alkaline rocks, and plagioclase and K-feldspar in a granitic rock (Fig. 18A). They may be weathered to complex gibbsite-bearing secondary structures in which internal boundaries of each primary mineral component have become indistinct. Most examples of amphibolite, mainly composed of randomly oriented needle-shaped crystals of amphibole surrounding smaller volumes of light minerals, commonly exhibit a texture consisting of areas of cryptomorphic ferruginous material enclosing small areas of residual quartz and secondary gibbsite after plagioclase. All ferruginous alteromorphs are imbricated in such a way that their original boundaries are no longer identifiable.

The development of crypto-alteromorphs is possible only where the internal textures or patterns of orientation of the alteromorphs are all similar. An assemblage of contiguous septo-alteromorphs (see below), whose individual septa are all characteristically oriented in preferential directions inherited from each individual primary mineral, does not constitute an assemblage of crypto-alteromorphs because the original boundary of each primary mineral can be inferred from the different and particular orientation of each group of septa or of each area occupied by a secondary smectite-group mineral (Fig. 18B). In contrast, assemblages of glomero-alteromorphs (see below) commonly give rise to crypto-alteromorphs because all individual secondary minerals are randomly distributed and randomly oriented in all the alteromorphs. The first case is common in completely weathered pyroxene- or hornblendite-rich rocks, under conditions of ferrallitic weathering, whereas the second case is more common, under similar conditions of weathering, in completely weathered feldspar-rich rocks such as anorthosite.

Potential crypto-alteromorphs can be observed in ultramafic rocks in which olivine and orthopyroxene grains are intimately associated. Both minerals may be weathered to very similar smectite-group minerals. In fact, they can only be easily distinguished from each other where the orthopyroxene-rich part of the assemblage exhibits the distinctive symplectitic texture, in which intergrowths with unweathered magnetite clearly show the original contacts between grains of orthopyroxene (with magnetite) and olivine (without magnetite) (Fig. 18C). Potential crypto-alteromorphs also may be found where alteromorphs after olivine exhibit traces of curved protoclastic fractures, whereas the alteromorphs after orthopyroxene exhibit traces of linear transverse fractures. If the optical orientation of the secondary products is different in the two alteromorphs, they are not classified as crypto-alteromorphs, but rather as groups of iso-alteromorphs.
FIGURE 18. Mode of formation of crypto-alteromorphs.

A. Three different primary minerals, and only one secondary mineral is produced
0: irregular assemblage of subhedral crystals of orthoclase and plagioclase with a subhedral crystal of biotite;
1: irregular pellicular and linear incipient weathering of the main primary minerals to gibbsite;
2: cavernous residues are isolated, with residual voids, between septa of gibbsite. Biotite weathers to kaolinite;
3: minute residues of feldspar, many residual voids and incipient weathering of the biotite - kaolinite to gibbsite;
4: glomerosoapic and linear textures without clearly recognized boundaries: CRYPTO-ALTEROMORPHS.

Note: The parallel linear texture and the interlaced deposits of iron oxyhydroxides allow the alteromorph after biotite to be clearly distinguished, in the cryptomorphic assemblage, from the alteromorphs after the feldspars. The feldspars start to weather along fractures, cleavages and twin planes; intermineral boundaries progressively tend to disappear.

B. Two different primary minerals, and only one secondary mineral produced, but in different orientations
0: an olivine crystal with its curved protoclastic fractures has grown in contact with a cleaved crystal of orthopyroxene;
1: nearly complete weathering of the olivine into ferrigenous smectite and incipient weathering of the orthopyroxene;
2: unordered texture of the smectite after olivine, and parallel banded texture defined by oriented particles of smectite after the pyroxene;
3: sparse dendritic residues of orthopyroxene within regularly oriented smectite; thin deposits of Fe oxyhydroxides along fractures and cleavages;
4: both minerals are completely weathered to smectite; they are CRYPTO-ALTEROMORPHS.

Note: The boundary between the alteromorphs is delimited only by the different orientations of the smectite. In the case of an olivine- and orthopyroxene-rich rock, the weathered rock can exhibit many assemblages of crypto-alteromorphs, whose origin is recognizable only by the orientation of the smectite and by the attitude of the original fractures.

C. One partly polyphase alteromorph (with primary mineral) and similar secondary products
0: a large crystal of olivine is partly replaced by a corona of a symplectic assemblage of hypersthene and magnetite;
1: incipient weathering of the residual core of olivine to a smectite along its protoclastic fractures;
2: complete weathering of the olivine core to smectite, whereas the symplectic corona is still unweathered;
3: partly weathered hypersthene to smectite whose composition is similar to that of the smectite after olivine;
4: both olivine and hypersthene are weathered to unoriented smectite: CRYPTO-ALTEROMORPHS.

Note: Only the presence of the original intergrowth with magnetite allows the smectite-bearing alteromorph after orthopyroxene to be clearly distinguished from the intergrowth-free alteromorph after olivine. This complex assemblage of minerals leads to the development of polyphase, polygenetic crypto-alteromorphs.
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

**EUHEDRAL CRYSTAL:**

**OLIVINE**
Kivu, Democratic Republic of Congo

Objective: x 6.3
PPL and XPL

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**EUHEDRAL CRYSTAL:**

**OLIVINE**
Sonora, Mexico
Sampled by L. Paz Moreno

Objective: x 6.3
PPL and XPL

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**EUHEDRAL CRYSTAL:**

**OLIVINE**

6-sided shape of a euhedral crystal of olivine in a basaltic rock. A thin rim of dark green saponite is irregularly developed around the crystal. The higher interference-color of the rim is an indication of a higher iron content.

Below, a skeletal (incomplete) euhedral crystal of olivine surrounded by a regular rim of reddish brown "iddingsite". Domains of basaltic groundmass are located inside the skeletal phenocryst. Note the anomalous interference-color, caused by dispersion of the optic axes because the crystal is cut nearly perpendicular to an optic axis.
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

203, 204
EUHEDRAL CRYSTAL: ORTHOPYROXENE
Koua Bocca, Côte d'Ivoire
Objective: × 6.3
PPL and XPL

205, 206
EUHEDRAL CRYSTAL: CLINOPYROXENE
Kivu, Democratic Republic of Congo
Objective: × 4
PPL and XPL

The euhedral crystal of orthopyroxene (hypersthene) is characterized by its pleochroism, in shades of pink. The crystal normally has a straight extinction, but the crystal shown has been fractured and slightly deformed by tectonic forces. The two halves of the prism are not exactly at extinction at the same angle of rotation of the microscope stage. Note the occurrence of many transverse fractures.

The euhedral phenocryst of clinopyroxene (augite) in a basaltic rock is cut nearly perpendicular to an optic axis. Consequently, its interference-colors are very low. Note the irregular inclusions of basaltic groundmass and the chemical zoning of the crystal, expressed by slight variations in color in both PPL and XPL photographs.
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

EUHEDRAL CRYSTAL: CLINOPYROXENE
Kivu, Democratic Republic of Congo
Objective: x 4
PPL and XPL

EUHEDRAL CRYSTAL: HORNBLende
Koua Bocca, Côte d'Ivoire
Objective: x 2.5
PPL and XPL

This example of a euhedral phenocryst of clinopyroxene (augite) in a basaltic rock shows sector zoning, each sector displaying particularly well-developed oscillatory zoning. During its growth, the crystal engulfed many small inclusions of basaltic material and broken crystals of augite.

Below, several euhedral crystals of hornblende and anhedral crystals of clinopyroxene are embedded in a poikiloblastic crystal of quartz. The two crystals of hornblende in contact exhibit the characteristic shapes of amphibole-group minerals. The grain is six-sided where it is cut perpendicular to the Z axis, and rectangular where it is cut parallel to the Z axis.
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

211, 212
SUBHEDRAL CRYSTALS:
PLAGIOCLASE
Visoke volcano,
Democratic Republic
of Congo
Objective: x 4
PPL and XPL

213, 214
EUHEDRAL CRYSTAL:
PLAGIOCLASE
Ribeirão Preto, Brazil
Objective: x 10
PPL and XPL

This sample of porphyritic basalt shows a typical glomeroporphyritic texture. Lath-shaped subhedral phenocrysts of plagioclase are clustered in aggregates of radiating crystals called glomerocrysts. They are enclosed by a fine-grained groundmass composed of olivine, augite, plagioclase and magnetite. They exhibit the characteristic elongate shape and albite polysynthetic twinning (locally combined with twinning according to the pericline and Carlsbad laws). See also the previous photographs 110, 111, 116 and 117.

The central part of this rectangular section of a zoned euhedral crystal of plagioclase is altered to an oxidized smectitic secondary product along its cleavages and fractures, whereas the external, more sodic part of the zoned crystal is much less affected by weathering.
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

**EUHEDRAL CRYSTAL: TITANITE**
Koua Bocca, Côte d'Ivoire
Objective: × 6.3
PPL and XPL

**EUHEDRAL CRYSTAL: EPIDOTE**
Koua Bocca, Côte d'Ivoire
Objective: × 10
PPL and XPL

TITANITE is commonly observed as an accessory mineral in many igneous rocks. Crystals are generally diamond-shaped, as shown here. Its shape, its brown color and its high relief make it easy to identify in thin section. Its very high birefringence and its dark color cause it to show a similar color in both PPL and XPL.

This well-developed crystal of epidote illustrates the typical shape of a euhedral crystal, achieved where it can freely crystallize before the surrounding minerals. Nevertheless, the crystal is not perfectly euhedral, as it contains many inclusions of quartz and plagioclase, trapped during the last stage of growth.
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

219, 220
EUHEDRAL CRYSTAL: GARNET
Brittany, France
Objective: × 4
PPL and XPL

221, 222
EUHEDRAL CRYSTAL: STAUROLITE
Port Cro, France
Objective: × 2.5
PPL and XPL

The euhedral crystal of garnet exhibits nearly all the characteristic features of members of this group. Coloration in shades of pink, a high relief, numerous inclusions, and radial or crossing fractures are clearly seen in PPL, whereas its cubic symmetry makes the grain isotropic and completely at extinction in XPL, whatever its orientation.

A euhedral six-sided prism of staurolite is cut nearly perpendicular to its Z axis. This orientation determines its first-order grey interference-color in XPL. Pleochroic in shades of yellow, staurolite is easily identifiable in medium-grade metamorphosed argillaceous sedimentary rocks. The mineral is very resistant to weathering.
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

EUHEDRAL CRYSTAL: PEROVSKITE
Tapira, MG, Brazil
Objective: x 10
PPL and XPL

EUHEDRAL CRYSTALS: Apatite and Pyrite
Koua Bocca, Côte d'Ivoire and Brittany, France
Objective: x 6.3 and x 16
Both views in PPL

The perovskite (orthorhombic, pseudocubic symmetry) exhibits in thin section some similarities with titanite, namely a high relief and a dark brown color. However, the presence of multiple twinning observed in XPL, a more roundish shape, and the mineral association of the host rock make perovskite (CaTiO₃) easily distinguishable from titanite (CaTiSiO₅).

Apatite (hexagonal symmetry) and pyrite (cubic symmetry) are common minerals of many igneous and metamorphic rocks. A prismatic habit with a hexagonal cross-section and a low birefringence in the case of apatite, and the opacity of the subhedral sections in the case of pyrite, make these minerals easy to identify in thin section.
A euhedral crystal of olivine is completely altered to a pseudomorph of saponite. No internal pores are distinguishable at the scale of the optical microscope. It would seem that the molar volumes of the primary and secondary minerals are similar, such that the resulting alteromorph is an iso-holo-pseudomorph. The orientation of the secondary particles of saponite is not uniform. Most particles are arranged according to a parallel banded pattern, which corresponds to internal cracks oriented perpendicular to the long axis of the original crystal of olivine, whereas the other clay-rich domains are oriented parallel to the plane of the thin section. The banded texture exhibits bright interference-colors, whereas the other domains are at extinction under XPL. The pleochroism of the saponite can be seen in PPL; the clay mineral is pale yellow where oriented perpendicular to the plane of the section, and brownish beige where oriented parallel to it. Such differences in orientation are very commonly observed in alteromorphs, whatever their mineralogical origin and the nature of the secondary mineral. The two circular black spots and the grey elliptical patch are artificial holes and an air bubble trapped by the cover glass, respectively.
Euhedral Crystals and Pseudomorphs

The term euhedral can also be applied to skeletal crystals, which have not reached their full development because of rapid growth, as in the case of this six-sided grain of olivine. The faces are well developed, but one dome face exhibits large regular re-entrants, whereas two other faces enclose elongate inclusions of matrix material. The groundmass of the basaltic rock also shows many skeletal, lath-shaped crystals of plagioclase, along with intersertal cryptocrystalline clinopyroxene grains. The olivine crystal is transformed to saponite. Its distribution and orientation are very similar to those in the two preceding photomicrographs. Whatever the orientation of the secondary minerals, the alteromorph is not considered to be polyphase, as the same species of secondary mineral occupies the entire volume of the original primary mineral. There is no modification of volume, and intramineral pores are absent. The alteromorph is a holo-pseudomorph.

229, 230
Basaltic rock
Ocean floor
Costa Rica Rift
Leg 70, site 504b
Sampled by C. Laverne
Pseudomorph after olivine
Objective: x 16
PPL and XPL

Atlas of Micromorphology of Mineral Alteration and Weathering
EUHEDRAL CRYSTALS AND PSEUDOMORPHS

231, 232
CALC-ALKALINE
granitic rock
Koua Bocca, Côte d'Ivoire
Sampled at outcrop
Pseudomorph
after allanite
Objective: x 16
PPL and XPL

A EUHEDRAL CRYSTAL of allanite (epidote group) has been completely weathered to poorly crystalized saponite under the influence of two processes. Metamictization, which strongly disrupts the crystal's structure, is due to the allanite's high content of radioactive elements. Near-surface weathering led to the preferential replacement of this damaged crystal. In PPL, the secondary product is regularly and concentrically distributed relative to the crystal faces whereas in XPL, the cryptocrystalline nature of most of the pseudomorph is expressed by a nearly isotropic character. The pseudomorph is irregularly surrounded by an incomplete rim of skeletal primary epidote. The surrounding rock-forming minerals are mainly quartz, plagioclase, apatite, present in small grains, and micas. In this rock, only the allanite crystals are completely weathered. Among the associated minerals, only the biotite is partially weathered, to saponite.

PART 3: ALTEROMORPHS

185
A six-sided crystal of olivine is altered to an irregular septa-alteromorph of fer­riteous residual secondary clays, whereas the inner volume of each cell is filled with radiating assem­blages of fibrous crystals of a zeo­lite-group mineral. Both secondary minerals have formed during the same late-magmatic stage, and they are associated in the same alteromorph. The result is a polyphase pseudomorph. Both secondary phases exhibit a specific orientation; the clay mineral seems preferen­tially oriented perpendicular to the septa and to the external margin of the primary crystal, whereas the fibrous crystals of zeolite are prefer­entially oriented in a radiating pat­tern.
235, 236

**Metagabbro**
Koua Bocca, Côte d'Ivoire
Sampled at outcrop
Echino-alteromorph after hypersthene
Objective: x 10
PPL and XPL

The original rock is composed of plagioclase, clinopyroxene and orthopyroxene, and minute grains of magnetite. Subjected to high-grade metamorphism owing to the emplacement of younger granites nearby, most rock-forming minerals of the original gabbro have been completely replaced by secondary minerals. The plagioclase is replaced by clinozoisite (colorless areas B2, B4), associated with a chlorite-group mineral (pale green areas, C5) where the border zone of the grains abuts grains of clinopyroxene. The clinopyroxene grains are replaced by actinolite, whereas the orthopyroxene is replaced by bundles of acicular crystals of tremolite associated with minute inclusions of magnetite (C3). Small grains of titanite (A2) and a few flakes of biotite (B2) have been formed during the metamorphic transformation of the rock. The original margins of the primary minerals have been partially obscured by the crystallization of the secondary products, but the position of each of them can be easily recognized. The central area (C3) shows an alteromorph after a prismatic crystal of hypersthene; the acicular crystals of tremolite that replace it are oriented parallel to the main axis of the original mineral, and many of them protrude beyond the limits of the primary mineral, giving rise to a good example of an echino-alteromorph.
In the contact area with the surrounding younger granites, the pyroxenite of the ultramafic igneous suite has been strongly recrystallized, and most of the original constituents have been replaced by secondary minerals. The aggregate of minerals shown in the central part of the photomicrograph is an alteromorph after orthopyroxene, composed of an irregular bundle of prismatic crystals of tremolite. The aggregate exhibits a more-or-less radiating or divergent pattern, and some crystals of tremolite have their terminations largely protruding beyond the original boundary of the primary mineral, emphasized by an irregular rim of minute grains of magnetite. During their growth, two prisms of tremolite have pushed aside part of the magnetite rim (E1). The tremolite penetrates the surrounding vermiculite, which is formed at the expense of large grains of phlogopite. The result is a typical echino-alteromorph. The other altered grains just visible in the upper left and in the lower right corners are also orthopyroxene crystals, entirely replaced by bundles of tremolite associated with minute crystals of magnetite. The magnetite contains the iron of the original hypersthene that has not been consumed in the formation of the tremolite. Consequently, these alteromorphs and the central echinomorph are polyphase alteromorphs.
ORTHOPYROXENE- AND Biotite-Rich PYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 1.2 m

An illustration of the further development of echino-alteromorphs
Objective: x 4
PPL and XPL

This altered rock has been sampled in the lowest part of the landscape, where the drainage is restricted and where, as a result, the rates of weathering are reduced. The rock, which is rich in orthopyroxene enclosed in large poikilitic crystals of biotite, has been altered by a hypogene process to iso-alteromorphs of talc after orthopyroxene and to meso-alteromorphs of vermiculite after biotite. The iso-alteromorphs are surrounded by a regular rim of secondary magnetite, corresponding to the iron of the orthopyroxene that does not enter the structure of the talc. These iso-alteromorphs after orthopyroxene are polyphase (talc + magnetite) alteromorphs. The volume increase of the surrounding vermiculite explains the opening of many interlayer voids. In XPL, the talc areas show a micro-aggregated texture and the expected second- and third-order interference-colors of talc, whereas the unidirectional arrangement of the vermiculite is obvious. The sizes and shapes of the alteromorphs of talc seem to be similar to those of the original grains of orthopyroxene. Consequently, they can be classified as iso-alteromorphs. As is common in most alteromorphs of hypogene origin, no residual voids are observed. The iso-alteromorph is also a holomorph. Note that the rim of magnetite clearly outlines each alteromorph of talc (see next photomicrographs, 240, 241).
The original rock is similar to that shown in the former photographs. Although the rock is strongly metamorphosed, the original texture is clearly recognizable. A rim of magnetite surrounds the alteromorphs after pyroxene; these rims are thinner than those shown in the previous illustrations, but the size, shape and distribution of the alteromorphs are similar. The higher grade of the hypogene process has resulted in the replacement of both primary orthopyroxene and biotite by the same secondary mineral: all needle-shaped crystals, regularly oriented through the area shown, consist of a monoclinic amphibole of the tremolite–ferro-actinolite series. Its nearly colorless appearance, in PPL, indicates that its composition is near that of tremolite. Most of the iron content of the orthopyroxene had previously been incorporated in the magnetite rims. Consequently, no more iron enters the composition of the amphibole-group mineral. Compared with photomicrographs 238 and 239, talc has disappeared, and a parallel texture replaces the radiating texture of the tremolite needles, but the preserved rims of magnetite allow the texture and the mineralogy of the original rock to be easily recognized. The tremolite needles protrude out of the alteromorphs after pyroxene, and continue into the neighboring alteromorphs after biotite; this justifies a classification of the alteromorphs as (reciprocal) echino-alteromorphs.
242, 243

GABBRO
Itapeva, SP Brazil
Sampled at outcrop
Echino-alteromorph after olivine and plagioclase
Objective: x 6.3
PPL and XPL

Two adjacent grains of olivine and plagioclase have been partially weathered to yellowish saponite and to colorless isotropic material, respectively. The result of this combined weathering can be described as an echino-alteromorph because the domains of saponite protrude from the original volume of the olivine, and penetrate the feldspar grain along the median planes of the digitate network of fissures filled with isotropic material. The saponite is regularly oriented as long as it is included within the original volume of the olivine, but it is devoid of regular orientation within the neighboring grain of feldspar, as can be clearly seen in the picture taken in XPL. A few denticulate remnants of olivine persist in part of the alteromorph (A3), whereas several remnants have been later weathered to hydrated oxides of iron. According to the distribution of all these secondary products, it is highly probable that this last step of weathering of olivine is contemporaneous with the weathering of the feldspar grain to isotropic material. In contrast, the digitations of saponite occurred in the early weathering step of the feldspar, at a stage when many radiating fissures, which are attributed to the increase in volume of the alteromorph after olivine, broke the then unweathered grain of feldspar.

PART 3: ALTEROMORPHS
These photographs are to be compared to the two preceding ones. In the median part of the thick oxidized cortex that surrounds the relatively unweathered core of the weathered boulder from which the preceding photographs were taken, the saponite domains are oxidized, and replaced by reddish brown secondary products whose optical characteristics are very similar to those of the commonly observed "ildingsite". The origin of this secondary product is made clear by the fact that all intermediate steps of coloration can be observed, the alteromorph after olivine being yellow in the core of the boulder and red in its cortex. This comparison allows the penetration of the saponite formed at the expense of olivine into the feldspar to be better visualized, although in this case, a grain of pyroxene (C3) is partly located between the olivine and the feldspar grains. Dark brown areas of iron oxyhydroxides are randomly distributed around the alteromorph after olivine and within the partially weathered rock. Note that the volume of the isotropic secondary product after feldspar has not increased compared to its volume in the earlier photomicrographs. It will be necessary to examine a thin section of the external part of the cortex to evaluate the further replacement of the isotropic material by gibbsite. These four photographs illustrate quite well the fact that olivine is the most weatherable mineral of the rock.
A small portion of olivine crystals has been weathered to brownish green secondary products of nontronitic composition. The intermineral boundaries of the original grains of olivine and the irregular intermineral and transmineral fissures have been the pathways along which dark brown deposits of iron oxyhydroxides have formed. The complicated network resulting from all these fissures and deposits makes the different alteromorphs indistinguishable from one another. Even under XPL, it is not possible to clearly distinguish the boundaries of all the original grains. Such a complex aggregate corresponds to an assemblage of crypto-alteromorphs. No residual pores are seen within the alteromorphs: they are consequently crypto-holo-alteromorphs. Note that some areas of secondary products after olivine either exhibit a constant orientation of their particles or do not exhibit any particular orientation. In certain cases, some areas exhibit two different (random and parallel) patterns of internal orientation. Crystals of the much less weatherable plagioclase are only partly affected along the intramineral cracks and along their twin planes.
Echino-, crypto-, phanto-alteromorphs

Objective: × 10
PPL and XPL

Diabase

Touba, western Côte d’Ivoire
Sampled by B. Boulangé
Cortex on a boulder

Crypto-alteromorphs after clinopyroxene and plagioclase

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Atlas of Micromorphology of Mineral Alteration and Weathering
**250, 251**

**AMPHIBOLITE**

*metadiabase*

Guarulhos, SP, Brazil

Sampled by M. Bergman at rock outcrop

Case I:

unweathered rock

Objective: x 4

PPL and XPL

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The next four are taken from one large sample that contains a large core of unweathered rock surrounded by a very thick cortex of completely weathered rock. The photomicrographs of the unweathered rock are shown here to better visualize how quickly a rock with typical and easily identifiable minerals and texture has become, under conditions of ferrallitic weathering, a completely weathered cortex; in it, both minerals and textures are those of a cryptomorphic assemblage in which the original minerals are no longer easily distinguishable. The unweathered rock is composed of bundles of green amphibole, irregular interstitial colorless islands of quartz and alkali feldspar, and opaque minerals. The amphibole consists of an assemblage of bundles of subparallel elongate crystals. Each bundle of amphibole crystals is diversely colored, in PPL, owing to the pleochroism of the mineral, which varies from dark green to pale yellowish green. Each amphibole bundle appears with its own general coloration because all its component crystals are oriented more or less parallel to each other, whereas their average orientation appears different relative to that in neighboring bundles. The boundaries of each amphibole crystal or assemblage can be clearly identified when carefully observed with medium to high magnification.
The thin transitional fringe (some mm thick) that separates the unweathered rock (250, 251) from its completely weathered cortex (254, 255). Most of the feldspar is replaced by irregular glomero-alteromorphs of gibbsite (A4, E1), whereas each crystal of the slightly less weatherable amphibole has undergone its own pellicular weathering to brown-colored oxyhydroxides of iron. Where more completely weathered, after the disappearance of the residual remnants, the bundles of all these partially developed alteromorphs will be turned into irregular assemblages of alveoporo-alteromorphs whose original margins, although maintained, will become indistinguishable from one another; they will have become assemblages of crypto-alteromorphs. The orientation of the particles of iron oxyhydroxides formed from each original crystal is not clearly seen because the original crystals of amphibole of each bundle are thin and oriented in subparallel fashion, and not strictly parallel to each other. Nevertheless, the common optical orientation of many amphibole remnants is clearly recognized in observations of each amphibole bundle separately. Many remnants exhibit the typical denticulate margins of partially weathered amphibole-group minerals. The opaque minerals (A4) are not yet weathered.
Case 3: completely weathered rock
Crypto-alteromorphs after amphibole

Objective: x 4
PPL and XPL

These two photomicrographs focus on the completely weathered cortex that surrounds the unweathered core and the intermediate fringe, illustrated above. No amphibole or feldspar remnants persist in this part of the weathered rock. Only residual quartz and opaque mineral grains are preserved. The weathered rock is composed of large brown-colored areas, derived from the original bundles of amphibole, now converted to iron-rich secondary products, and of irregular colorless areas composed of residual quartz and feldspar, the latter now converted to assemblages of crypto-glomero-alteromorphs of gibbsite. Both colored and colorless areas have given rise to irregular cryptomorphic assemblages of secondary minerals: hydrated oxides of iron, which originate from the weathering of the amphibole-group mineral, and gibbsite, which originates from the weathering of the feldspar grains. Note that halos of colored material have invaded the gibbsite-rich areas by irregular dissemination of iron-rich compounds, whereas no gibbsite crystals are clearly distinguished in the iron-rich areas formed at the expense of amphibole (the small birefringent crystals in these dark areas are very small grains of quartz). The weathered rock, whose original mineralogical and textural patterns have become obscured, is now converted to a complex assemblage of two distinct domains of crypto-alteromorphs.
shows a micaceous mineral, the original species not identifiable, completely weathered to a kata-alteromorph of kaolinite that has been partially replaced by iron oxides during a later step of iron accumulation. This later process is responsible for the disappearance of most of the alteromorph, now reduced to traces of a fan-like assemblage of residual and deformed layers of iron-free kaolinite. The shapes and colors of the residual minerals contrast with those of the more homogeneous iron-rich matrix; a typical phanto-alteromorph results.

The lower photomicrograph shows a phanto-alteromorph in which some thin irregular relics are barely visible in the iron-enriched matrix of a tropical iron crust. Observations in the lower part of the profile show that it results from an early step of mesomorphic alteration of a crystal of phlogopite to vermiculite which, during a later step of weathering, has been partly weathered to a second meso-alteromorph of kaolinite. The latter still contains many interlayered remnants of vermiculite, now replaced by iron-rich material, recognizable by its contrasting dark brown color. The interlayered kaolinite has completely disappeared where replaced by the less ferruginous, pale brown matrix.
Anorthosite
Near Porto Allegre, Rio Grande do Sul, Brazil
Depth: 1.5 m
Phanto-alteromorphs after plagioclase
Objective: × 4
XPL

This accumulation invades parental or partially weathered fragments of rock, the plagioclase grains are irregularly replaced by the microsparite. The grains are gradually reduced to smaller and smaller residual fragments. Most fragments maintain their original crystalline orientation, but some of them may also be slightly rotated, which is expressed by the different interference-colors exhibited, under XPL, by neighboring fragments. Regardless of the degree of preservation of the original grains, their original shapes and boundaries are no longer discernible because the epigenetic process progresses not only along the intramineral fractures, but also along the intermineral suture planes. The extensive fragmentation of most grains and the disappearance of most original margins make the resulting alteromorph a typical phanto-alteromorph.
The rock, whose main constituents are diopside and phlogopite, is partially replaced by microcrystalline calcite (microsparite), which develops at the expense of nearly all minerals of the rock, especially the calcium-rich minerals such as diopside. Phlogopite, which is calcium-free, is essentially unaffected by this process; it remains clearly recognizable as undisturbed domains isolated within a largely replaced groundmass. Such portions of unaltered phlogopite are visible in the left upper and lower corners of the photomicrographs. The largest area of the photograph exhibits a grain of diopside that is partially replaced by aggregates of unoriented microcrystals of calcite, which appear grey in PPL and brownish beige in XPL. The colorless remnants of unaltered diopside exhibit their second-order interference colors in XPL. Note that all remnants of clinopyroxene exhibit a denticulate shape and an undisturbed common orientation. Some cracks (as near the center of the crystal) are filled with coarse crystalline calcite (sparite). Where more advanced and where several contiguous grains of clinopyroxene are observed, their own original limits will be recognized only with difficulty, because the orientation of the secondary calcite is uneven and not influenced by the crystallographic orientation of the replaced mineral.
A primary mineral has been completely weathered to oxyhydroxides of iron. The original boundary of the alteromorph has been largely obscured by the later replacement of the iron compounds during the formation of the iron crust. The internal morphology has also been destroyed by successive episodes of recrystallization of the secondary crystallplasmas and by the opening of newly formed internal pores. Traces of several transmineral fractures are easily recognizable within the alteromorph: a large fracture (C2) has its two walls coated by iron oxides, whereas a large empty pore is maintained in the median plane of the fracture; several more transmineral fractures are clearly seen near the right lower edge of the alteromorph, but their walls are joined together without leaving any central pore. Traces of septa (B2) are more or less distinguishable within the areas between the fractures, but their pattern is not sufficiently preserved for unambiguous identification of the primary mineral. It may have been either clinopyroxene, orthopyroxene, or amphibole. In view of its size and shape, the phanto-alteromorph must have originated from the weathering of a coarse-grained prismatic crystal of a ferromagnesian mineral. The material that surrounds the phanto-alteromorph does not contain any trace of the original textures of the parent rock.
A portion of primary silicate minerals has been completely weathered to a cluster of very porous alteromorphs, mainly composed of dark brown iron-rich products. The weathered rock is now a thick iron crust (more than two meters thick), developed in the upper part of the profile; the original textures of the rock have completely disappeared. These alteromorphs, most of whose original margins are no longer easily distinguishable, give rise to an assemblage of crypto-alteromorphs. They are embedded within a secondary iron-rich plasma that does not seem to be formed at the expense of in situ primary minerals, but rather corresponds to allochthonous infillings of a large cavity produced by the weathering of a vein of hydrothermal origin. The observation of more thin sections of the profile, and mainly of the slightly weathered rock from a depth of several meters, indicates that the original rock is crossed by numerous veinlets of quartz, chlorite and epidote. These observations allow the nature of the primary mineral to be recognized, because neither the shape nor the composition of the alteromorphs, such as they are observed within the iron crust, are fully characteristic. A comparison with the unweathered veinlets indicates that the chlorite-group mineral has been completely weathered, and that its soft secondary products were dispersed and eroded, whereas the harder iron-rich alteromorphs have resisted to internal erosion. The epidote is an iron-poor primary mineral. This is the reason why alteromorphs formed at the expense of epidote grains are highly porous; the irregular ferruginous septa correspond to the radial fractures and to the twin planes of the original grains. Several alteromorphs have lost their original shape, and were partly destroyed by erosion; several residual intramineral pores have been invaded by allochthonous secondary products. Under these conditions, an identification of the alteromorphs as phanto-alteromorphs seems to better correspond to the partly destroyed residual textures. Some residual grains of quartz (D1) are still maintained within the pale brown secondary plasma.
Complex meta-cumulo-phanto-alteromorph after plagioclase

Objective: x 6.3
PPL and XPL

observed in the upper part of the profile, results from the successive influences of alternating weathering and accumulation under conditions of ferrallitic weathering. A comparative study with samples lower in the profile allows the chronology of the successive events to be established. The plagioclase is first weathered to a gibbsite-rich glomero-septo-alteromorph. Higher in the profile, the residual voids are infilled with allochthonous kaolinite. As the voids are gradually infilled, the gibbsite is dissolved, leaving more and more empty spaces for illuviation by kaolinite. The traces of the original twin planes and intramineral cracks of the feldspar are progressively enriched in dark brown iron oxyhydroxides. During a later step, in the upper level of the profile, the allochthonous kaolinite is weathered, and replaced by a new generation of "autochthonous" gibbsite, giving to the complex alteromorph a new alveoporo-glomero-alteromorphic texture. The brown coloration of the gibbsite-rich areas, in PPL, is due to the iron content of the illuvial kaolinite. In XPL, colorless rims of relatively coarse crystals of gibbsite, in an iron-depleted rim around the residual empty pores, contrast strongly with the microcrystals in the glomero-alteromorphic texture. The rectilinear ferruginous septa are the only textural feature of the previously formed septo-alteromorph to be preserved in this more recently degraded phanto-alteromorph.
CHAPTER 8

The Content of Alteromorphs

Alternomorphs exhibit regular or irregular, homogeneous or heterogeneous internal textures that are independent of the degree of preservation of the shape and size of the original minerals. These textures are closely related either to dissolution processes, which determine the volumes of the secondary products and of the complementary secondary voids, or to the internal pattern of the primary minerals (fractures, cleavages and twins). Such features influence the progress of weathering reactions affecting the primary mineral and, as a result, the distribution, orientation and micromorphology of the secondary products (Fig. 19). Whatever the degree of preservation of the original shapes and volumes, the completely developed alteromorphs may be classified firstly according to the total volume of the secondary

![Diagram of Alteromorphs]

**Figure 19.** Definitions of alteromorphs on the basis of microtextural criteria, i.e., the complementary distribution of the secondary products and of the residual pores within the alteromorphs. For further criteria of classification, see Figures 23 and 27.
voids, regardless of their distribution and organization, and secondly, according to their inherited or neoformed internal textures, which control the complementary distribution of the solid neoformed products and the residual voids.

**THE PROPORTION OF SOLID AND PORE VOLUMES**

Alteromorphs are first classified according to the ratio of the volume of their secondary products to that of their residual voids. Most residual voids are formed within the alteromorphs, and peripheral residual voids surrounding the secondary products are rarely observed. Where they are, they probably result from the opening of a previously existing intermineral void.

**Holo-alteromorphs**

Holo-alteromorphs (from the Greek ὅλος = whole, full, complete) correspond to fully developed alteromorphs in which the volume of the secondary minerals is apparently equal to the original volume of the primary mineral. The volume of the possible micropores is not perceptible at the scale of the optical microscope, and it is not taken into account.

The secondary phase exhibits a dense and homogeneous aspect, with or without particular internal textures due to variations in grain size or orientation of the secondary minerals. Holo-alteromorphs are generally produced by peripheral centripetal weathering of poorly cleaved and unfractured minerals under conditions of leaching that do not promote the extensive removal of the original soluble constituents. In this case, the volume of the voids is minimal (Fig. 20).

Where the primary mineral is not cleaved or fractured, the resulting holo-alteromorph is homogeneous, not only in its chemical and mineralogical composition, but also in its internal texture. This is the case, for example, of the weathering of a pyrite grain to iron oxide. In contrast, where the primary mineral is fractured or cleaved, the resulting alteromorph may exhibit some microtextural heterogeneities. The occurrence of fractures and cleavages in the primary mineral promotes the development, along these planes, of better crystallinity or of a preferred orientation or a greater compaction of the secondary microparticles.

Nontronite-rich holo-alteromorphs after fractured olivine commonly exhibit such microtextural differentiations. The hypogene alteration of forsterite (olivine-group mineral) into talc may give good examples of holo-alteromorphs in which the secondary talc may exhibit perceptible differentiations of the size and orientation of its elementary particles. Some holo-alteromorphs of "iddingsite" after olivine may exhibit an internal reticulate banded network of more compact or more strongly colored "iddingsite". In this case, the network, whose distinct formation is due to the occurrence of protoclastic fractures, may become enhanced by minute deposits of early-formed magnetite.

The holomorphic character of an alteromorph is independent of its mineral content. Aggregates of secondary products may consist of one or two (or more) distinct mineral species. The criterion of differentiation of the holo-alteromorphs is based only on the absence of perceptible residual voids.

**Koilo-alteromorphs**

Koilo-alteromorphs (from the Greek κοίλος = empty, hollow) correspond to empty alteromorphs, without any secondary mineral, developed by weathering of a soluble mineral (Fig. 21). The outline of a koilo-alteromorph is ephemeral, and corresponds to a part of the outline of adjacent mineral grains. The definition of a koilo-alteromorph may be extended to an alteromorph whose content of residual material does not exceed 2.5%.

**Figure 20.** Relationship of a holo-alteromorph to a grain of a primary mineral.
Koilo-alteromorphs are ephemeral because they have suspension by vertical or lateral transport. These may occur either during or after the weathering of the mineral. If the infilling is synchronous with weathering, the potential koilo-alteromorph does not develop, and the identification of its origin is easy if examples of ephemeral coexistence of primary mineral residues and first-formed infillings are observed. Even where ephemeral two-phase alteromorphs are not observed in the thin section, the nature of their infilling material will be similar to the infilling material of fractures and pores of the surrounding alteration. Therefore, the allochthonous origin of the infilling material is suggested, and the presence of potential koilo-alteromorphs is confirmed. The nature of the infilling material may be in geochemical discordance with the composition of the observable residues of the primary mineral. Where such geochemically discordant alteromorphs are observed, the occurrence of potential koilo-alteromorphs at the expense of completely soluble minerals may be suspected, and the allochthonous origin of the infilling is confirmed.

Those alteromorphs that contain only infilling materials of allochthonous origin are cumulo-(koilo-)alteromorphs (see below). Their origin will be identified only with difficulty without residues of the primary mineral in the alteromorph concerned or in similar neighboring alteromorphs.

Calcite and dolomite (with a low content of the ankerite and rhodochrosite components) may produce, upon complete weathering, practically empty koilo-alteromorphs containing only small quantities of residual insoluble iron or manganese hydroxides. These hydroxides reflect the low level of Fe or Mn substituting for part of the Ca or Mg in the primary mineral. Apatite crystals commonly give rise to koilo-alteromorphs surrounded by a thin rim of brown deposits owing to the precipitation of allogenic iron oxyhydroxides in the phosphate-rich contact area.

Koilo-alteromorphs may persist for a long time if the soluble minerals from which they developed are relatively few and isolated in the parent rock. The presence of slightly weatherable or unweatherable surrounding minerals, with persistent outlines and resistant volumes, allows the empty volumes of the koilo-alteromorphs to persist until these surrounding minerals also are weathered and have crumbled. In contrast, if the soluble minerals are the main constituents of the rock, as in calcareous rocks (such as limestones, marbles and carbonatites), the derived koilo-alteromorphs are ephemeral, because they have no mechanical resistance. Koilo-alteromorph-rich alterites are soon subjected to settling and compaction, and the inherited structures and textures consequently disappear.

Within horizons of absolute accumulation, or during a later stage of weathering, koilo-alteromorphs may become infilled owing to the later crystallization or deposition of material transported in solution or in suspension by vertical or lateral transfer. These allochthonous infillings may occur either during or after the weathering of the mineral. If the infilling is
have developed by the later complete dissolution of quartz grains, whose remnants do not persist and whose residual empty volumes are never infilled by allochthonous material; comparison with neighboring samples, in which the quartz is only partly dissolved, commonly permits confirmation of the derivation of these kollo-alteromorphs.
A Falk Hypomagrite process has altered an olivine crystal into reddish brown “iddingsite”, and a typical holo-alteromorph results: no residual pores are observed at the scale of the optical microscope. The small specks, colorless in PPL (BC2) and extinct in XPL, are sections of thin prismatic crystals of apatite. Another crystal of apatite, lying in the plane of the thin section (C4), is barely visible through the transparent “iddingsite”. The original network of protoclastic fractures of the primary olivine has been perfectly preserved during the transformation of the mineral; it appears as criss-crossing dark lineaments that divide the grain and delimit several adjacent domains of secondary products. More recently developed transmineral fractures give rise to opaque deposits of allochthonous manganese oxides. Note that several domains of “iddingsite” adjacent to these fractures have also been stained by a coating of iron compounds, which gives them a dark red color. The original color of the “iddingsite” is that of the more external parts of the alteromorph. In spite of this late modification, the optical orientation of the whole alteromorph is homogeneous, and its extinction between crossed polars (not shown) is simultaneous in all its domains. Where they persist, both the remnants of olivine and the secondary “iddingsite” usually extinguish together (straight extinction). The grains of clinopyroxene are slightly weathered to saponite, which surrounds denticulate residues (D4).
A holo-alteromorph of olivine has been completely altered, under the influence of hypogene processes, to an association of talc and magnetite. The association of these two minerals is commonly encountered, and the resulting alteromorph after olivine is a polyphase alteromorph, as both minerals, talc and secondary magnetite, have formed together during the same hydrothermal step. The minute grains of magnetite are mainly developed within the rim of the alteromorph, and they are related to the original iron content of the olivine, which has not all entered the structure of the talc. Minute grains of magnetite are also distributed according to a linear pattern that corresponds to the network of protoclastic fractures of the primary crystal of olivine. No intramineral pores are observed, at the scale observable with an optical microscope; it is a holo-alteromorph. In XPL, the minute particles of talc are randomly oriented through most of the alteromorph, whereas relatively coarse crystals of talc are regularly oriented. This orientation is probably related to the crystallographic orientation of the original olivine. However, since no olivine relics are observable within the alteromorph, this hypothesis cannot be proven. Such an alteromorph clearly shows a typical composite pattern of orientations and distribution of the secondary products.
OLIVINE-BEARING CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 10.2 m
Holo-alteromorph after olivine
Objective: x 6.3
PPL and XPL

The crystals of olivine isolated within this clinopyroxene-rich rock are completely weathered to holo-alteromorphs of saponite, whose layers are regularly arranged in a parallel set of thick lamellae. The volume and number of the residual pores, visible at the scale of the optical microscope, are very small, and are probably due to imperfect impregnation of this sample, in which most minerals are not weathered. The saponite layers exhibit their usual yellow colors in PPL. In XPL, the parallel stacking of the layers and their uniform orientation are expressed by the uniform second- and third-order interference-colors over the entire holo-alteromorph which, for these illustrations, has been rotated to the angle of maximum illumination. The original crystal of olivine was broken by several protoclastic fractures, regularly coated by a thin deposit of magnetite, which is now weathered to irregular brown patches. Coarse opaque grains of magnetite, inside (D2) or outside (D5) the olivine crystal, are apparently not weathered. The surrounding grains of clinopyroxene (A3, E3) show incipient weathering (denticulations and emphasized cleavages), whereas part of the biotite has been replaced by reddish brown secondary products (D5). Owing to the mesomorphic alteration of the mica it contains, the rock is fractured by transmineral and intermineral cracks (A1, A4, E2).
A fragment of perovskite (CaTiO₃), commonly associated with magnetite or ilmenite or both, has been completely weathered to secondary microcrystalline anatase (TiO₂), whereas the calcium content of the original mineral has been leached away. The associated magnetite (E5) is not, or barely, weathered. The grain size of the anatase is different according to location in relation with the intramineral microfissures. As can better be seen in XPL, the size of the crystals is much greater along the internal fissures whereas, within the irregular cells delimited by these fissures, the anatase is chiefly cryptocrystalline. The intra-alteromorphic pores are due to the dissolution of apatite or carbonate inclusions, and not to the formation of the alteromorph at the expense of the original perovskite. The brown color in PPL and the bright yellow color in XPL are characteristic of anatase; they are rather similar to the colors exhibited by some other titaniferous minerals, such as rutile.
273, 274

Olivine-bearing clinopyroxenite
Koua Bocca, Côte d'Ivoire
Depth: 11.2 m
Holo-alteromorph after olivine
Objective: x 6.3
PPL and XPL

A group of olivine, composed of two joined crystals whose respective orientations differ, is completely altered to saponite, whose regular optical orientation is strongly dependent upon the original orientation of the primary crystals of olivine. The orientation of the secondary mineral in the lower left part of the alteromorph, which is bright yellow in PPL, is nearly parallel to the plane of the thin section, whereas in the upper right part of the alteromorph, beige-colored in PPL, the orientation is more or less perpendicular to this plane. Both orientations are confirmed by the interference-colors, in XPL: very low colors, nearly at extinction, for the first part of the alteromorph, and second-order colors for the second one. These photomicrographs illustrate the fact that the crystallographic orientation of the secondary products can be strongly dependent on the crystallographic orientation of the primary minerals, although this must not be generalized to all alteromorphs formed at the expense of all primary minerals. Since no intramineral residual pores are observed within these joined alteromorphs, the alteration process has given rise to holo-alteromorphs.
An alteration process of olivine has been replaced by a holo-alteromorph of saponite under the influence of a late-magmatic process. The original network of protoclastic fractures of the primary crystal, with their content of minute grains of magnetite, is still clearly distinguishable as randomly oriented black-colored alignments. These strongly contrast with the yellowish orange color of the secondary clay mineral. Only one secondary mineral has been formed during the alteration process. Since no intramineral residual pores are discernible, the resulting alteromorph is consequently not a polyphase alteromorph, but rather a normal (monophase) holo-alteromorph. The small roundish colorless crystals included within the alteromorph are primary crystals of apatite. Note the conspicuous pattern of internal distribution of optical orientations of the saponite. This unusual pattern, which appears only in XPL, is rarely encountered.

Along the protoclastic fractures, irregular banded patterns have been formed in which the optical orientation of the secondary products is quite different from that of the main volume of the alteromorph.
Dissolved or residual grains of quartz may become trapped in old ferrallitic iron crusts formed on the deep weathered profiles developed on ultramafic rocks. Under conditions of ferrallitic weathering, these iron-rich rocks may develop a very thick weathered mantle, whose upper part is subjected to intense leaching of silica, with concomitant relative accumulation of the insoluble components such as iron, aluminum and titanium. The aluminum content of the primary rock (4% Al₂O₃) is too low to allow the formation of important aluminum-rich residual materials, whereas their high iron content promotes the formation of thick, hardened covers of iron-rich crusts in which the unweatherable residual minerals may become trapped. The quartz originates from the numerous veins of quartz and microgranite that cut the ultramafic intrusion. The residual quartz grains are completely encased in the crust in such a way that their boundaries are perfectly molded by the surrounding iron-rich matrix. With later reaction under new geochemical conditions, these quartz grains are slowly dissolved, without formation of any residue. Once they are completely destroyed, they form true koiloalteromorphs whose volume and shape closely correspond to the original volume and shape of the grains that disappeared. The photomicrograph shows, in its central part, a partially dissolved grain of quartz. Cavernous residues are scattered within a large residual pore whose volume and shape correspond to those of the original grain before it was dissolved. If a quartz grain is broken into several fragments, each residual fragment is free to move in the cavity, and the isolated fragments lose their common optical orientation. The photomicrograph of a completely dissolved grain of quartz, leaving an empty koiloalteromorph, would have been of lesser interest, because nothing could be left to prove that the cavity had really been formed by the dissolution of a quartz grain.
A aggregate of quartz is partly weathered by congruent dissolution along irregular cracks and patches: empty open dissolution-induced pores are formed, either within the quartz grains or along the intergranular boundaries. The occurrence of several distinct component quartz grains is attested to by the fact that they do not exhibit the same interference-colors in XPL. The dissolution-induced pores are efficiently filled by relatively coarse crystals of gibbsite of allochthonous origin; these do not occupy all the available volume of the residual pores. The alignment of the gibbsite crystals in the fractures and cracks does not form true continuous septa; the crystals exhibit a random optical orientation. Where gibbsite crystals form infillings of more extended areas, as in B–C3, they exhibit a glomeromorphous texture of joined but randomly oriented crystals. The difference between primary autochthonous and secondary allochthonous minerals is enhanced, in the photomicrograph, by the fact that the thin section is slightly thicker than usual, which leads to higher interference-colors for the gibbsite crystals. They appear as yellowish domains, whereas the original quartz cores have maintained their first-order grey interference-colors in XPL. Without these infillings by allochthonous gibbsite, the dissolution of the polycrystalline quartz assemblage would have promoted the formation of a koilo-alteromorph. The occurrence of these infillings will make this alteromorph a cumulo-(koilo)-alteromorph once all domains of residual quartz have disappeared.
The granite rock is strongly affected by conditions of ferro lithic and bauxitic weathering: the plagioclase and orthoclase are converted into gibbsite-bearing glomeruro-septo-alteromorphs, and the quartz grains are partly dissolved, leaving residual empty pores. The weathered horizon is then subjected to illuviation of allochthonous materials coming from the upper part of the profile. The quartz grains are fractured and partly dissolved; empty cracks and dissolution pores surround smoothly shaped cavernous residues. The photomicrographs show how a partly dissolved grain of quartz is filled up progressively as it is dissolved; a peripheral rim is formed, and crystals of gibbsite are aligned around the intermineral boundaries and along the first-formed fractures. After this first step of infilling by gibbsite, the progressive dissolution of the quartz leaves more and more empty peripheral dissolution-induced pores. The pore space between the quartz residues and the first-formed gibbsite rims then is infilled by iron-rich allochthonous material. Infillings can alternate or can be incomplete or externally distributed. A second generation of gibbsite deposits is observed in some more recently formed residual pores. The shapes of the concentric rims of gibbsite seem to be related to the successive shapes of the dissolved quartz grain.
The photomicrographs illustrate another example of a quartz grain that has been partly dissolved, and whose residual empty pores have been progressively infilled by allochthonous material as the volume of the residual cores decreased. Thin rims and alignments of small crystals of gibbsite also are observed around the alteromorph, as in the previous photomicrographs, but in this case, the infilling material is mainly composed of iron-rich secondary material. The roundish cavernous residues of quartz are highly fractured, and the irregular network of internal cracks is also infilled by the brown-colored secondary allochthonous material. The photograph taken in XPL shows the compactness and the acetic* fabric of the iron-rich material, and the distribution of more recently formed peripheral pores, immediately adjacent to the quartz residues; these pores are not yet infilled by the allochthonous material.

Bauxitic Profile
developed on granite
Siagozohoin, Lakota,
Côte d'Ivoire
Depth: 3.8 m
Sampled by B. Boulangé
Cumulo-koilo-alteromorph
after quartz
Objective: × 6.3
PPL and XPL
Among the common rock-forming minerals, apatite and calcite are certainly the best examples to illustrate the behavior of very soluble minerals and the formation of residual koilo-alteromorphs. But the presence of ephemeral residues in the area photographed is necessary for a better understanding of the weathering process and the mineralogical evolution of the alteromorph. The photomicrographs show relatively small crystals of apatite that are partially weathered. Irregular residual fragments are temporarily maintained within large pores, whose outlines obviously correspond to the outlines of the original crystal. Thin deposits of iron-rich compounds form a thin rim around the koilo-alteromorph. The iron does not originate from the apatite, which is iron-free, but from the intermineral aqueous solutions which, in contact with the phosphate- and calcium-rich environment of the weathering apatite, precipitate part of their iron content. The rim has an allogetic origin; it is probably mostly fixed as a rim external to the original surface of the apatite crystals. Once completely weathered, the final alteromorph will be a true koilo-alteromorph whose mineralogical origin cannot be deduced from anything but their size, shape and distribution, in contrast to less weathered samples.
The upper photomicrograph, in PPL, shows the end-product of weathering of an apatite-rich carbonatite. Grains ofankerite have been dissolved, giving rise to large koi-lo-alteromorphs, but their low content of iron has led to the formation of a dark brown rim around most of the koi-lo-alteromorphs. The high concentration of apatite of the original rock has allowed the original texture to be maintained in the completely weathered rock, and has promoted the later crystallization of a second generation of apatite within the koi-lo-alteromorphs. The lower photomicrograph, in XPL, shows the residual, less weathered crystals of partly recrystallized apatite (A1, E3), whose glomeroloalteromorphs exhibit sizes and shapes comparable to those of the koi-lo-alteromorphs after ankerite (B–C3). The secondary apatite forms needle-shaped crystals, mostly arranged according to a radial texture; these are fixed on the residual ferruginous rims, whose slenderness and brittleness are considerably increased. Only the presence of these first and second generations of apatite crystals has allowed the isalteritic character of the completely weathered rock to be maintained. The second generation of apatite crystals has an extra-alteromorphic origin; the koi-lo-alteromorphs that host them are cumulo-koi-lo-alteromorphs.

The objective: X
PPL and XPL

0.6
0.4
0.2
0.0 mm
"Poro"-alteromorphs

"Poro"-alteromorphs (from the Greek πόροι = pores) form a group of alteromorphs transitional between the two extreme cases described above, in which the ratio of discernible voids is important compared to the volume of newly formed minerals with which these voids are genetically associated (Fig. 22). In practice, this general term is not to be used as a single term, but it is proposed only for the introduction of the next items. "Poro"-alteromorphs are porous or pore-bearing alteromorphs; they are not entities that result from the infilling of a pre-existing external pore, nor entities that exhibit the shape and size of a pore.

The voids observed within the alteromorph must be genetically connected with the secondary material of the alteromorph. Therefore, this newly coined term cannot be used to describe entities that result from the infilling of a pre-existing void (vesicle in a basaltic rock, miarolitic cavity) or of a more recently formed pore (e.g., pedotubule, channel, of pedological or biological origin). In order to avoid any confusion, the term "poro"-alteromorph is never used; the term "poro"-alteromorph, with the prefix "poro" in quotation marks and without additional prefix, can be used to convey a more general meaning.

"Poro"-alteromorphs constitute the main group among the alteromorphs because most primary minerals, whatever the process of weathering, develop intimate associations of secondary products and residual voids. At constant volume, the alteroplasmas and residual voids are complementarily proportioned and distributed.

Depending on the complementary proportions of the solid phase and included voids, "poro"-alteromorphs can be described (and new terms can be introduced) either according to (a) the pattern of voids, if these are few or small, and if they exhibit a characteristic pattern of distribution within an important continuous solid phase, or (b) the pattern of the solid phase, if its volume is smaller than that of the voids, and if the solid phase is the one that exhibits the characteristic pattern.

Pore Volume as a Distinguishing Criterion

The term "poro"-alteromorph pertains to a group of porous alteromorphs. It cannot be used as a single term, and it must necessarily be preceded by a prefix that describes the main features of the pores, their number, their shapes, their distribution and their spatial relationships with the solid phase (Fig. 23). Several specific "poro"-alteromorphs can be distinguished.

Alveoporo-alteromorphs

Alveoporo-alteromorphs (from the Latin alveolus = cell, small cavity) are characterized by the occurrence of irregular pores that are distinctly discernible at the scale of the microscope, and whose total volume is considerably smaller than that of the alteroplasma. The pores correspond to inner volumes, and they are invariably surrounded by the alteroplasma (Fig. 24).

The volume of the discernible pores is smaller than that of the solid phase; commonly, the alveolar pores are randomly distributed, and they exhibit uneven shapes (e.g., lenticular, elliptical, denticulate, amorphous). They are located within an abundant and continuous alteroplasma whose texture and crystallinity may be homogeneous or not. Around the alveolar pores, a rim of crystalliplasma* commonly is formed. By the size and, in some cases, the orientation of its constituents, the rim contrasts sharply with the more uniform habit of the micro- or cryptocrystalline parts of the alteromorph (Fig. 24).

Alveoporo-alteromorphs generally result from the weathering, under conditions of moderate leaching, of uncleaved and unfractured minerals. The importance of the total volume of the pores is proportional to the quantity of dissolved and leached elements, which thus are not incorporated into the crystal structure of the secondary minerals. In general, these pores represent...
Figure 23. Definitions of alteromorphs on the basis of micromorphological criteria: the classification of the "poro"-alteromorphs according to the distribution of voids.
the final stage of evolution of perinuclear* and interplasma - mineral* pores developed in partly weathered minerals. They are located at the sites from which the last remnants of the residue have disappeared. Where not disturbed by external processes, this internal pore-space is generally not connected to external pores. As a result, it is rarely infilled by later deposits of allochthonous origin.

Following the number of distinct internal pores, the alveoporo-alteromorphs can be divided into mono-alveo-, oligo-alveo- and poly-alveoporo-alteromorphs (respectively, from the Greek μονονυς = one, alone, ολυνυς = few, and πολυνυς = many, several).

This intramineral porosity may also result from later alteration of a (non-porous) kolo-alteromorph, whose alteroplasma itself is modified by irregular degradation and incomplete dissolution of its mineral constituents. In this case, the aspect (color, micro-porosity, crystalinity and orientation) of the surrounding part of the alteroplasma, around the alveolar pores, may differ greatly from the original aspect of the first-formed alteroplasma. They are meta-alveoporo-alteromorphs (from the Greek μετα = after, latter), if a genetic concept is added to the morphological description (see below).

Alveoporo-alteromorphs may be genetically very different, even where they exhibit very similar patterns, and where the clear distinction between them is not always obvious. If the alveolar pores are directly formed during the weathering of the primary mineral, and if all the secondary products belong to this first generation, the alteromorph is an ortho-alveoporo-alteromorph. If the alveolar pores are derived from the late partial degradation or dissolution of the first-formed secondary products, the alteromorph is termed a para-alveoporo-alteromorph. It is obvious that this case can occur only where the first-formed secondary products are themselves weatherable (smectitic secondary products, for example). The inner fringes of the newly formed alveolar pores commonly are rimmed by iron-rich secondary products or by other highly contrasting materials of a second generation.

**Centroporo-alteromorphs**

*Centroporo-alteromorphs* (from the Latin centro- = center, middle) are characterized by the occurrence of a single large pore, located in the central part of the alteromorph, completely surrounded by a continuous rim of alteroplasma, which is generally formed by peripheral centripetal weathering of a homogeneous primary mineral. Its location within the alteromorph and its shape are generally determined by the position and shape of the last residual core before its complete disappearance, whereas its size is generally determined by the relative proportions of soluble and insoluble elements contained in the parent mineral.

This is the typical case of a mono-alveoporo-alteromorph. This particular type of internal porosity is common in alteromorphs developed by weathering of small, unsplit and unfractured grains of primary minerals. The residual volume of the primary mineral progressively decreases by peripheral centripetal weathering. Simultaneously, the thickness of the rim of alteroplasma and that of the perinuclear void both increase. The chemical elements that do not enter the mineralogical makeup of the alteroplasma are leached out, and their removal is responsible for the main part of the residual pore. The chemical elements that make up the minerals of the alteroplasma must be transferred from the surface of the remnant to the surrounding rim through the inter-plasma - mineral void. Where the leaching and removal of the chemical constituents are very important, the volume of the residual products may be very small. A continuous thin film of secondary products is developed along the internal surface of the alteromorph. That particular pattern of distribution makes the alteromorph very similar to a kolo-alteromorph.

The external outline of the rim on the alteroplasma generally follows intermineral boundaries. Its pattern is simple, more or less polyhedral, and linear. In contrast, its internal outline may be either smooth and regular, which gives a rim of constant thickness, or irregular and denticulate, which gives, at least in detail, a rim of irregular thickness.

Small grains of pyroxene and amphibole, where completely weathered, commonly exhibit such a pattern, with a denticulate central pore.
Indeed, at the beginning of weathering, when the alteroplasma is still in contact with the primary mineral from which it developed, the direction along which weathering preferentially develops, as well as the alignment and orientation of the secondary minerals, are strongly influenced by some crystallographic directions of the primary mineral. The central primary residue exhibits a finely denticulate outline in one direction, against which the first-formed secondary particles were tightly molded. The empty perinuclear void, which develops later and which is progressively widened, maintains the particular pattern of denticulation until the remnant of residue has disappeared. It is possible to recognize the original optical orientation of the primary mineral by observing the orientation of the inherited denticulation and, in addition, the common crystallographic orientation of all the secondary particles that compose the alteroplasma.

Centroporo-alteromorphs are particularly common in medium- and fine-grained rocks that are weathered under conditions of efficient leaching. Where the weatherable minerals are abundant in the rock and where they contain small quantities of insoluble elements (such as in forsterite, diopside, enstatite, tremolite), the central pore may be voluminous relative to the thickness of the peripheral rim of secondary minerals. Their alterites are very porous, and may have a low density (≤ g/cm³).

Coarse crystals (e.g., phenocrysts, porphyroblasts) weather more slowly than smaller ones; as a result, their residues can persist for a longer time in the weathered profile. During the first stage of weathering, at the lowest level of the profile, where conditions of restricted drainage prevail, these crystals may be partly replaced by a thin rim and internal ribbons of smectitic clay along their inner fractures and cleavages. Without any modification of the drainage conditions, the coarse residues would weather to a homogeneous holo-alteromorph or to a phyllo-poro-alteromorph, whose secondary product would consist of a homogeneous smectite-group mineral.

In contrast, at the higher levels of the profile, the conditions of weathering are different, and the processes of leaching are more extreme. The residues, until then preserved, are no longer weathered to a smectitic clay, but directly to iron oxyhydroxides or even to a residual empty pore. In the first case, the iron-rich compounds crystallize as an internal rim against the first-formed rim of smectite, leaving a residual central pore. In the second case, an alveolar empty pore is formed directly, without a new generation of secondary products. In both cases, a centro-poro-alteromorph is formed. The first is a two-phase (smectite-group mineral + iron oxyhydroxides) centroporo-alteromorph, whereas the second one is a normal single-phase (smectite-group mineral only) centroporo-alteromorph (see below for the definition of the single-phase and two-phase alteromorphs). Since the iron oxyhydroxides are formed by weathering of the primary residues and not by later degradation of the first-formed secondary products, these alteromorphs are ortho-centroporo-alteromorphs.

More commonly, the coarse-grained primary crystals are crossed by transverse fissures that determine the isolation of several remnants and, consequently, of several alveolar pores (oligo-alveoporo- or poly-alveoporo-alteromorphs). Each of these alveolar pores may be later rimmed by iron oxyhydroxide, produced either by the weathering of the last primary remnants (ortho-alteromorphs) or by concomitant degradation of the first-formed secondary products (para-alteromorphs).

The central pore, well protected by a continuous rim of alteroplasma, is generally closed and without connection to the external macro pore-space as long as it is not disturbed by external physical or chemical processes.

**Phylloporo-alteromorphs**

Phylloporo-alteromorphs (from the Greek φυλλόν = sheet) are characterized by a regular distribution of elongate, planar or thinly lenticular and parallel pores whose volume is somewhat smaller than that of the solid phase. The pores may be continuous or discontinuous, and are parallel to one of the axes of the alteromorph. Their direction is generally inherited from the primary mineral where it is a mica, whose perfect cleavage is the determining factor, or from crystallographic orientation where the primary mineral is a ferromagnesian phase; in this case, its structure determines the orientation of the porous aggregate of secondary phyllosilicates (Fig. 25).

This particular type of layered microtexture is common in alteromorphs that develop by weathering of micaceous primary minerals, which directly determine the distribution and orientation of the secondary products. The microtexture also may arise by weathering of other primary minerals, such as pyroxenes and...
amphiboles, to alteromorphs in which well-oriented flakes of a smectitic clay are the main constituents. Either the primary mineral or the secondary mineral can be responsible for the orientation of the phyllo-
pores.

An example of the first case is provided by the weathering of biotite or phlogopite to smec-
tite- or kaolinite-rich alteromorphs. The sheets of the secondary silicate are well oriented parallel to the sheets of the primary mineral, even where weathering has promoted a mesomorphic or a katamorphic transformation. The pore-space thus opened commonly is developed by the sepa-
ration of thick layers of primary or secondary sheets under the influence of internal stresses
during the formation of an expanded altero-
morph, or under the influence of a later swelling of the secondary clay by hydration.

An example of the second case is provided by the weathering of a pyroxene. Under condi-
tions of restricted drainage, an alteromorph com-
pased of a smectite-group mineral will consist of particles strongly oriented parallel to the Z axis of the primary mineral. The resulting phylloporo-
alteromorph is regularly textured, and the inter-
layered pore-space, which is much thinner than in the previous example, is strongly oriented, con-
tinuous and parallel.

In both examples, the porosity along interlayers may be connected with the nearby intermineral pore-
spase and with fissures and fractures commonly devel-
oped around the meso- and kata-alteromorphs. The intramineral porosity can easily be filled by products of later crystalization or by deposits of allochthonous origin. Crystallization of bands of gibbsite, kaolinite, calcite or quartz is common in the phylloporo-alteromorphs derived from the alteration or weathering of micaceous minerals.

The distinction between generations of kaolinite, for example, commonly is easy. The sheets of kaolinite formed by weathering of primary biotite are parallel to its foliation, whereas the sheets of the infilling kaolinite have a tendency to crystallize perpendicular to the sheets of the mica. This is also the case for the crystals of quartz, or even of gibbsite, of allochthonous origin.

These compound alteromorphs are cumulo-phyllo-
poro-alteromorphs (see below).

Infillings of lenticular pores by quartz, calcite
even titanite have also been recorded in phyl-
loporo-alteromorphs derived from the hypogene altertion of micaceous minerals. They also can be classified as cumulo-phylloporo-alteromorphs. Where observed in a plane parallel to the layer-
ing of the mica, these lenticular infillings of quartz or calcite may appear as circular or elliptical bod-
ies, whose constituent crystals in some cases exhibit a radial distribution.

Deposits of autochthonous origin can also occur within the phyllo-pores. These secondary products are derived from the primary mineral itself, but consist of chemical elements that have not entered the structure of the main secondary product. Needles of sagenitic rutile or microparticles of iron oxyhydroxide commonly occur as thin deposits regularly distributed within the phyllo-pores of vermiculite or kaolinite alteromorphs after a Fe- and Ti-bearing mineral like biotite.

This kind of porosity can also result from the arti-
ficial shrinkage of a foliated secondary phase during the preparation of the thin section. Obviously, this artificially created pore-space is invariably empty and, nor-

mally, it does not contain allochthonous material. Note that artificial deposits of abrasive material may be present.

**Retiporo-alteromorphs**

Retiporo-alteromorphs (from the Latin reticulum = network) are alteromorphs in which voids are distributed according to a three-dimensional net-
work of planar open fractures that cross in sub-

orthogonal directions. These fractures exhibit a constant or hierarchical thickness, and divide the solid phase into isolated polyhedral volumes of comparable shapes and sizes (Fig. 26).

This particular texture is not common, but it can occur under specific conditions of weathering. It seems to be the result of the natural dehydration, shrinkage and subdivision of an originally continuous and homog-
eneous hydrated solid phase. The more strongly
The retiporo-alteromorph thus is an ephemeral kind of alteromorph (gradual polyphase alteromorph). It is later replaced by a more common type of alteromorph, such as a glomero-alteromorph or a septo-alteromorph (see below, Figs. 41, 42).

These reticular structures are easily filled by allochthonous material derived from the neighboring weathered minerals or from a higher horizon. These infilling materials may thus be the same as the autochthonous secondary minerals. The identification and description of the resulting complex textures and of the chronology in their development are not always easy.

**The complex pattern of weathering of nepheline**

In the case of the weathering of nepheline, for example, the empty reticular network that develops in the isotropic, amorphous, secondary material is progressively filled by regular alignments of allochthonous microcrystals of gibbsite. Each volume of the isotropic solid phase may persist for a long time before also being replaced by autochthonous microcrystals of gibbsite, which develop peripherally at the expense of each volume of the isotropic phase. At the end of the weathering stage, the first-formed retiporo-alteromorph is replaced by a gibbsite-rich polygenetic glomero-septo-alteromorph. The septa consist of the first generation of allochthonous gibbsite, whereas all the inner polyhedral volumes are replaced by a second generation of aggregated autochthonous crystals of gibbsite, formed by peripheral evolution of the isotropic phase, which regularly surrounds a central alveolar residual pore. The complex alteromorph results from the superposition of three successive processes: (1) a retiporo-alteromorph is formed, which (2) later is filled by allochthonous material (it is converted to a cumulo-retiporo-alteromorph); the geochemical evolution of the isotropic material (3) finally gives rise to a very complex cumulo-alveo-retiporo-alteromorph.

Similar "retiporous" textures can be produced by the late evolution of vesicles and glass in a basaltic rock. A somewhat similar texture also can be observed in the nucleus of ferruginous or bauxitic nodules (see below), which can become divided according to radially oriented and concentrically distributed patterns of shrinkage-induced fissures.

Note that the reticulate texture can also develop by artificial shrinkage of hydrated material as a result of exaggerated desiccation of the weathered sample during the preparation of the thin section.
In the lower part of the profile, under conditions of restricted drainage, several randomly oriented crystals of clinopyroxene have been completely weathered, peripherally and centripetally, to well-oriented packets of clay. Each alteromorph exhibits its own orientation according to that of the Z axis of the precursor grain. During most of the weathering process, the pyroxene has been directly weathered to saponite without the formation of residual pores between the secondary product and the residual cores of pyroxene. The narrow interlayer pores are typical of phylloporo-alteromorphs, as will be shown in photomicrographs 292 and 293. At the end of the weathering process, under conditions of less restricted drainage, the residues of pyroxene have been dissolved, without producing anything but irregular residual pores, which gives complex alveo-phylloporo-alteromorphs. Although all residual cores have completely disappeared during this last step of weathering, the orientation of the secondary products allows the original boundaries of the primary mineral to be easily recognized, and the optical orientation of the grains to be easily deduced. In contrast, without knowing the nature of the original rock from studies of neighboring thin sections, it is not possible to determine the nature of the original pyroxene. Both orthopyroxene and clinopyroxene give way, once weathered, to alteromorphs whose secondary products are oriented parallel to the Z axis of the primary mineral. The orthopyroxene in these rocks is generally prismatic and coarse-grained. Consequently, alteromorphs after orthopyroxene clearly show the traces of fracturing of the mineral and of the early-formed banded textures that have resulted. Note that the alveolar pores are situated in the central part of the alteromorphs, and that they have an irregular shape and size. Their walls are denticulate, in a similar way as were the denticulate remnants before their disappearance. Iron oxide or hydroxide has not been formed during the last step of the weathering of the residues; they would be expected where the residues are subjected to more oxidizing conditions (see next photomicrographs).
The following photograph illustrates a case of clinopyroxene weathering that is very similar to the previous one. The first step of weathering corresponds to the formation of a partly developed phylloalteromorph, whose secondary products are well molded against the residues of pyroxene, without perinuclear pores. The secondary products are well oriented parallel to the z axis of the primary mineral. With increasing intensity of weathering, the pyroxene residues are then dissolved, without the formation of a smectitic secondary product, as in the previous case. The more oxidizing conditions found in the upper horizons lead to the precipitation of iron oxyhydroxides, and to the development of quasi-coatings* of colored material due to influx of iron and staining on the inner parts of the secondary products, whose coloration increases progressively as the residues are dissolved. The resulting alveoporoalteromorph, which is composed of two different secondary products (the early-formed smectite and the later-formed iron oxyhydroxides) can be considered as a polyphase alteromorph (see later). Note the irregularities of the pores, the disappearance of most of their denticulate border, and the gradual coloration of the smectite from the walls of the pores inward.
This example is very similar to the previous one, but the alteromorph is cut perpendicular to the Z axis of the clinopyroxene, not parallel to it. Both sets of perpendicular cleavages are normally observable in such a section. Since it is only developed according to a direction parallel to the Z axis and not along the cleavage planes of the primary mineral, the denticulation of the residual cores of clinopyroxene and of its secondary products is largely obscured in such a section. Traces of these cleavages can be distinguished within the secondary products. Alveolar pores are numerous and randomly distributed. They correspond to numerous and very small residues that have disappeared by dissolution after the formation of the smectitic material and during the development of the aureolar coloration of the pores by permeation of the iron compounds. Note that even in such a section, the smectitic secondary products appear as well-oriented particles throughout the alteromorph. In a thin section that would be cut according to a NE-SW direction, in this alteromorph, the orientation of the layers of smectic and its maximum interference-colors would be clearly observed, whereas in a cut parallel to the layering (NW-SE), the layered texture of the secondary product would disappear, its interference-colors, in XPL, would be very low, and the alteromorph would appear as nearly at extinction.
Phylloporo-alteromorphs after Clinopyroxene

Objective: × 10
PPL and XPL

Clinopyroxene have been completely weathered to a smectitic clay mineral of saponitic composition. No primary residues are present in the alteromorph, whose internal texture corresponds to that of a regular phylloporo-alteromorph. The thin regular pore-space is only distinguishable at high magnification. The regularity of the pores is mainly due to the fact that all secondary particles are well oriented parallel to the Z axis of the primary mineral. As a result, each alteromorph exhibits its own orientation of the secondary products and of the interlayered secondary pores. Some defects and alveolar pores are observed in some alteromorphs; they are due to the late disappearance of the residual remnants of primary pyroxene and to early-formed transverse fractures. This kind of phylloporo-alteromorph after clinopyroxene is generally observable only where the primary crystals are not too coarse; otherwise, the residual remnants of clinopyroxene are maintained high up in the weathered profile, and they are directly weathered to iron-rich secondary products, giving rise to polyphase or polygenetic alteromorphs. Here, the primary interstitial phlogopite has been replaced by yellowish vermiculite, whereas the magnetite inclusions are not yet weathered.
The upper photomicrograph shows the typical pattern of a phylloporo-meso-alteromorph. Many pores still exhibit a biconvex lenticular shape, whereas with more advanced leaching of the iron-bearing compounds in the internal part of the alteromorph, the residual thick layers are microdivided. Thin dark brown iron-rich layers are regularly interlayered with thin beige-colored layers of kaolinite.

The lower photomicrograph (to be compared with 174, 175) shows a comparable but inverse microtextural pattern, which is promoted by a similar process. In this case, the areas that have been the most iron-enriched are the walls of the previously formed transmineral fracture, which crossed the biotite crystal in a direction perpendicular to the sheets. Expansion is then restricted to a banded surface that crosses perpendicularly the sheets of the mica. This results in a moderate expansion of the iron-poor and weaker internal parts, whereas the iron-rich and more resistant transverse band is fractured. The resulting configuration is somewhat inverse to that shown in the previous illustrations: the residual expanded parts of the mineral are elliptical, whereas the pores are delimited by a biconcave outline.
ALVEOPORO-, PHYLOPORO-, RETIPORO-ALTEROMORPHS

296, 297
COARSE-GRAINED AMPHIBOLITE
Southwestern Côte d'Ivoire
Depth: 3.6 m
Retiporo-alteromorph after feldspar
Objective: x 10
PPL and XPL

A sample of coarse-grained amphibolite from southwestern Côte d'Ivoire at a depth of 3.6 m shows a retiporo-alteromorph after feldspar. The secondary material is divided into several pieces by an irregular network of open intramineral fractures. These fractures exhibit a somewhat hierarchical pattern, and their walls are mainly accordant surfaces. Each part of the divided secondary phase is in turn irregularly crossed by a number of thin fractures of second and third order. This successive fracturing is due to a process of progressive dehydration of the isotropic material. The reticular network of pores generates a typical retiporo-alteromorph. The yellowish color of the secondary product, in PPL, is caused by permeation of an iron-bearing solution from the neighboring grains of ferromagnesian minerals, mainly green hornblende, whose weathering is incipient, with oxyhydroxides of iron penetrating into the network of intersecting cleavages. The isotropic character of the secondary product after feldspar is proven by observing the second photomicrograph, taken in XPL.

Some patches of crystallized material appear within the retiporo-alteromorph; they are small crystallaria of gibbsite, which normally develop later at the expense of the ephemeral and transitory isotropic material. The sample was taken at the base of a profile showing ferrallitic weathering.
Apatite grains of feldspar have been completely weathered to an intermediate isotropic secondary product in the lower horizon of a ferrallitic profile. The rock is composed of coarse-grained plagioclase and hornblende. Owing to the difference in weatherability of the two primary minerals, the plagioclase can be completely weathered, whereas the hornblende still seems practically unweathered. The occurrence of numerous grains of completely weathered plagioclase gives to the partially weathered rock a crumbly texture, which is emphasized by the networks of closely spaced fissures within their alteromorphs. As in the earlier photomicrographs, the isotropic material is largely fragmented by a hierarchical network of fissures and fractures, which gives to the alteromorph a typical retiporo-alteromorphic pattern. Some open transmineral fractures are infilled by microcrystalline material of allochthonous origin (deep yellow material in PPL). It consists of a smectitic clay mineral. A detailed observation of the internal microtexture of these deposits shows that most crystallites have grown perpendicularly to the walls of the fractures. Their deposition is a consequence of crystallization in situ from an ionic solution. Very few patches of gibbsite are observed within the isotropic material.
The parent rock (lujaite) contains prismatic or needle-shaped crystals of aegirine, equidimensional or euhedral coarse crystals of nepheline, and large areas of eudialyte as main constituents associated with variable amounts of arfvedsonitic amphibole and tabular or lath-shaped crystals of orthoclase. As accessory minerals, rinkite ("mosandrite"), astrophyllite, lamprophyllite and complex titanium and zirconium silicate minerals are commonly observed. The photomicrographs show a completely weathered crystal of nepheline that has been replaced by an intermediate isotropic material whose microtextural pattern is very similar to the previously shown retiporo-alteromorphs after feldspar. The alteromorph is surrounded by large crystals of eudialyte (A5, E5), by a grain of orthoclase (E1), and by numerous external inclusions of needle-shaped aegirine. Within the alteromorph, many small unweathered inclusions of pale brown rinkite can be seen. The reticular network of hierarchical fractures and fissures is particularly well developed in this retiporo-alteromorph. Note the occurrence of small irregular patches of microcrystalline gibbsite along the contact area with the orthoclase crystal and within the alteromorph after nepheline.
NEPHELINE SYENITE
Pedra Balao,
Poços de Caldas,
MG, Brazil
Depth: 0.5 m
Retiporo-alteromorph after nepheline
Objective: x 6.3
PPL

This photomicrograph illustrates another particularly well-developed example of a retiporo-alteromorph formed at the expense of a nepheline crystal that has been completely weathered to an intermediate and ephemeral isotropic secondary product. The purpose of this photomicrograph is to show the regularly distributed and randomly oriented fractures and fissures in a typically well-hierarchized network. The larger are the open fractures, the older they are. In such a way, the alteromorph material is successively divided in fractal fashion into smaller and smaller fragments, which increases the bulk porosity of the weathered rock and decreases its apparent density. Once the weathered minerals will come into contact at the accumulation front with the aluminum-bearing solutions derived from the upper part of the profile, the network of pores of the retiporo-alteromorph will be infilled by allochthonous deposits of gibbsite, whereas the isotropic material will be, in turn, dissolved in order to generate more gibbsite in the next lower part of the profile. This leaves a cellular septo-alteromorph, which will be the negative picture of the previously formed retiporo-alteromorph (see later, 430 and 431, for the complete weathering of nepheline to gibbsite).
These photomicrographs illus-
trate the special case of the
weathering of poorly crystalline and
amorphous materials. The first
example corresponds to the weath­
ering of cryptocrystalline basaltic
glass that is interstitial among pla-
gioclase phenocrysts, whereas the
second one illustrates the weather­
ing of vesicular glass to brown-col-
ored palagonite. The basaltic glass
that surrounds the vesicles is not
very weathered; it exhibits an inter-
nal texture composed of many fans
of very small diverging needles of
plagioclase set in a vitreous ground-
mass. These photomicrographs clearly show how an isotropic
hypocrystalline or amorphous
material is divided into many angular
volumes by the formation of a
recticular network of fissures, which
progressively are widened as weath­
ering progresses. Most open fissures
are hierarchized, the widening of
the first-formed fissures taking
place as more thin fissures are
formed. The pattern of the reticular
network is better developed and
more regular in the case of vesicular
basaltic glass, which is perfectly
isotropic and which does not con-
tain any cryptocrystalline material.
The distribution of the secondary minerals in the alteroplasmas and in the crystalliplasmas commonly exhibits a particular microtexture (Fig. 27). This texture reflects, on the one hand, the conditions under which the primary minerals were weathered and, on the other, the internal structural discontinuities of these primary minerals, along which the first-formed secondary products may have been distributed. Some micromorphological features are thus directly inherited from specific features of the primary minerals.

**Figure 27.** Definitions of alteromorphs on the basis of microtextural criteria: the classification of the "poro" alteromorphs according to the distribution of the solid phases.
These microtextures are also porous; however, the organization and distribution of the voids are not diagnostic, but they clearly appear only if they are considered as complementary features of the solid textures. Only the solid volumes are to be discussed here. Consequently, the prefix "puro" is no longer necessarily included in the newly coined terms used to describe such alteromorphs.

**Botryo-alteromorphs**

Botryo-alteromorphs (from the Greek βρυχος = grape, cluster) are characterized by an internal structure consisting of homogeneously distributed and sized (sub)automorphic crystallites (or clusters of crystallites) of secondary minerals, which are stacked side by side, leaving among them small interstitial interconnected voids morphologically similar to packing voids (Fig. 28).

The volume of the interstitial voids may still be important, because most crystallites that compose the alteromorph are isolated from each other by interstitial interconnected voids. The crystallites are generally comparable in size throughout the entire alteromorph, although in the plane of the thin section (and as a rule for all stacking structures in which each crystal is not necessarily cut along its equatorial plane), some crystallites may seem smaller and surrounded by wider voids.

This microtexture commonly develops during the weathering of small grains of iron-bearing minerals such as olivine, pyroxene or garnet, which form alteromorphs partly infilled with small spherules of radiating needles of goethite. These small spherules are generally closely spaced and in mutual contact, and they delimit small triangular interstitial voids (tetrahedral in three dimensions), with curved sides. This texture can also develop within the empty pores of septo-alteromorphs. It also develops by weathering of grains of feldspar which, by evolution of an intermediate phase of homogeneous amorphous material, gives rise to isolated subhedral microcrystals of kaolinite or gibbsite. These booklets of kaolinite and single crystals of gibbsite are regularly distributed in the alteromorph. They are clustered in such a way as to have between them small polyhedral interstitial "packing" voids.

The botryomorphic texture is highly porous, and its internal pore-space is interconnected. Near the periphery of the alteromorph, the internal pore-space is commonly directly connected with the fissure-related pore-spaces of the alterite. It thus easily becomes filled with materials of allochthonous origin. During a later stage of infilling by processes of absolute accumulation, the characteristic internal structures of the botryo-alteromorphs may either become obscured and even disappear. This will happen where the imported material has the same mineralogical composition as that of the receiving texture. On the other hand, it may remain clearly distinguished if the material transferred has a different mineralogical composition, or if it exhibits a sufficiently distinct color or microtexture. In this last case, the botryomorphic elements of the alteromorph may appear as a mosaic-like assemblage of isolated crystals completely embedded within the cumulomorphic part of the alteromorph. Botryo-alteromorphs of gibbsite or kaolinite alter feldspar may possess a striking contrast if the voids are filled with a hematite-rich deposit.

**Glomero-alteromorphs**

Glomero-alteromorphs (from the Latin glomerare = to agglomerate), are alteromorphs in which individual crystals of supergene origin show a tendency to agglomerate into small, compact and irregular areas separated by large interconnected vughs. Within the solid volumes, the individual crystals are assembled into a pore-free (at the scale of the microscope) microgranular texture (Fig. 29).

The texture of the glomero-alteromorph is very similar to that of the botryo-alteromorph, but the distribution and, ultimately, the proportions of the interstitial voids differ. In the botryo-alteromorph, the
pores are numerous, small, isolated and interstitial, whereas in the glomero-alteromorph, the pores appear as a few large, interconnected vughs. The very small interstitial voids in the agglomerated areas, not visible at the scale of the optical microscope, are not taken into account. In the first texture, most crystallites are isolated, or they are in contact at a few points, whereas in the second case, most crystallites are agglomerated and in contact along the major portion of their outlines.

Whatever the distribution and organization of the voids, their volume is appreciable. In most cases, the pore-space is quantitatively more important than is the volume of the solid phase. These alteromorphs are as a result more common in the weathering of minerals subjected to conditions of strong leaching, which promotes the removal of the major portion of the chemical constituents originally present.

Discontinuous traces of the original fractures or incomplete septa commonly are recorded within the glomero-alteromorphs; these give rise to complex glomero-septo-alteromorphs.

For example, the weathering of feldspar grains under ferrallitic conditions usually gives rise to complex alteromorphs. On the one hand, well-oriented crystals of gibbsite are regularly juxtaposed to form septa whose organization corresponds to the network of original fractures. On the other hand, unoriented crystals of gibbsite are clustered, leaving empty vughs among them. The formation of the gibbsite-bearing septa along the original fractures always precedes the formation of the clusters of gibbsite formed at the expense of the residual remnants. Consequently, a partly developed septo-alteromorph forms before the agglomerated part. According to the order of formation of the structural elements in the final alteromorph, for cases where all residues are weathered, the order of the prefixes must be written as glomero-septo-alteromorph, and not as septo-glomero-alteromorph (see below, the case of complex poro-alteromorphs).

**Septo-alteromorphs**

Septo-alteromorphs (from the Latin septum, pl. septa = partition, compartment) are characterized by an internal fabric in which all the secondary minerals are distributed in banded textures (septa), among which empty, isolated polyhedral voids are enclosed. Most septo-alteromorphs are illustrations of the so-called "boxwork" texture (Fig. 30).

For example, the weathering of feldspar grains under ferrallitic conditions usually gives rise to complex alteromorphs. On the one hand, well-oriented crystals of gibbsite are regularly juxtaposed to form septa whose organization corresponds to the network of original fractures. On the other hand, unoriented crystals of gibbsite are clustered, leaving empty vughs among them. The formation of the gibbsite-bearing septa along the original fractures always precedes the formation of the clusters of gibbsite formed at the expense of the residual remnants. Consequently, a partly developed septo-alteromorph forms before the agglomerated part. According to the order of formation of the structural elements in the final alteromorph, for cases where all residues are weathered, the order of the prefixes must be written as glomero-septo-alteromorph, and not as septo-glomero-alteromorph (see below, the case of complex poro-alteromorphs).
The orientation of the elementary monocristals that compose a septum may be uneven. In this case, this lack of preferred optical orientation is observed in all septa and throughout the whole septo-alteromorph. Simultaneous extinction, under crossed nicols, of all single crystals making up a given alteromorph is never observed.

The orientation of the single crystals may be perpendicular to the median plane of the septum whatever its orientation; in this case, the orientation of the crystals follows all the windings and irregularities of the septum. If the septa of a given alteromorph are irregularly curved, only the crystals that are parallel to the optical planes of the microscope will go to extinction under crossed nicols, and the extinction of the septa will be undulatory. Single crystals do not go to extinction simultaneously along the whole septum. The partial extinction of the septo-alteromorph exhibits a dark cross that persists when the stage of the microscope is rotated, all individual single crystals being successively suitably oriented parallel to the optical planes of the microscope.

The orientation of the single crystals also may be controlled by the orientation of crystals of the primary mineral itself. In this case, all the secondary crystals of a given septo-alteromorph exhibit the same general orientation in all parts of the septum, and in all septa of the alteromorph, whatever the orientation of the septa. As a result, the extinction of the septo-alteromorph is complete and simultaneous in all its parts when the optical directions of the single crystals are suitably oriented with regard to the optical planes of the microscope. At 45° to these planes, the birefringence of the whole septo-alteromorph is maximum; this is the most suitable position for photomicrography.

The first two cases, especially the second one, are commonly observed in septo-alteromorphs of gibbsite after feldspars. The internal microstructure of each septum consists of two parallel layers of subparallel crystals on both sides of the median plane (which represents the trace of a pre-existing fissure). These crystals are arranged more or less perpendicular to this plane. Thicker septa in some cases consist of two or more successive layers of gibbsite crystals. The regular orientation of the gibbsite crystals is nevertheless slightly obscured, in thin section, by the fact that gibbsite has a monoclinic symmetry, and thus an oblique extinction. Furthermore, most crystals are twinned. This case of regular orientation of the secondary minerals is also very common in the septo-alteromorphs of goethite developed at the expense of iron-rich garnet.

The third case is more commonly observed in septo-alteromorphs developed at the expense of iron-rich minerals, such as those of the pyroxene and amphibole groups. As soon as the weathering of these minerals begins, the secondary crystallites of iron oxyhydroxide are strongly oriented parallel to the Z axis of the primary mineral, whatever the orientation of the fractures or cleavages along which weathering began. Thereafter, once the septa are thickened by material transfer, the regularity of orientation of the crystallites tends to decrease slowly with increasing distance between the residual remnants on one hand, whose volume rapidly decreases, and the newly formed septa, whose thickness slowly increases. Be that as it may, the uniform orientation of most secondary crystallites promotes a perceptible extinction of the whole septo-alteromorph upon rotation, under crossed nicols, to a position parallel to the Z axis of the primary mineral.

The pores that are delimited by the septa are generally polyhedral volumes with planar or curved faces; they are theoretically closed volumes and largely inaccessible to transmineral transfers. Some septa may be discontinuous; they may be interrupted, and several adjacent polyhedral pores may be interconnected.

The volume of the voids may be much greater than that of the secondary phase. The thickness of the septa depends, on one hand, on the conditions of weathering, which determine the volume of the exported elements and, as a result, the volume of the residual pores. On the other, thickness depends on the chemical composition of the primary mineral, which determines the proportion of the immobile elements. The richer in immobile elements the primary mineral, the thicker will be the septa of its alteromorph, and the smaller will be the proportion of internal residual voids. In this way, the alteromorphs formed at the expense of different kinds of primary pyroxenes in a weathered pyroxene-rich rock can easily be distinguished (Delvigne 1965).

All these septo-alteromorphs possess the so-called "boxwork" texture. Septo-alteromorphs that consist of iron or aluminum hydroxides are chemically and mechanically resistant, because they are supported by a strong three-dimensional network of stable secondary minerals. Consequently, they can persist for a long time, not only within the isalteritic horizons of the lateritic profiles, in which the septo-alteromorphs are particularly abundant, but also within alloteritic horizons, and even within weathered lithorelics (alterorelics), which occur in soil horizons, in colluvium and in ferruginous and bauxitic duricrusts. At these
different levels of weathering, the interseptum pore-space may be filled by later products of crystallization or deposition of dissolved constituents or material transported over long distances (from higher horizons or from upper parts of the landscape).

Depending upon the original network of fissures, cracks, cleavages and other structurally imposed directions in the primary minerals, and in accordance with the previous classification of partly weathered minerals (Stoops et al. 1979), boxwork textures can be described as irregular or as regular septo-alteromorphs. It is obvious that even within the so-called regular septo-alteromorphs, the observed textures are not always perfectly developed; many small accidents may locally interrupt their regularity. For example, small interrupted septa may occur as branches on main continuous septa or as isolated fragments (bridged in the third dimension) within the polyhedral voids. The combination of a regular cleavage and irregular fractures may promote the formation of complex septo-alteromorphs (see below). The septa corresponding to fractures generally develop before those developed along a cleavage.

Irregular septo-alteromorphs correspond to an uneven arrangement of the septa, without any particular distribution or orientation, controlled by the patterns of fissures and cracks developed in the uncleaved primary mineral.

The discontinuities that control the distribution of the septa correspond mainly to transmineral and intramineral fissures and to transverse* fractures. Intramineral fissures play a similar role, and the alteromorph commonly is completely surrounded by a polygonal and peripheral rim of secondary products, whose internal texture is somewhat different than that of the internal septa. The peripheral "septum" does not contain a median plane against which the two layers of crystallites are symmetrically organized, as is the case for the common internal septa. Instead, it consists of only one layer of secondary products; as a result, its thickness is generally less than the thickness of the internal septa.

Where adjacent septo-alteromorphs have the same mineralogical composition because they are developed from the same primary mineral, the conjoined peripheral rims can simulate the usual organization of a septum by the simultaneous development of identical secondary products on both sides of the intermineral fissure. Where these peripheral rims and internal septa are incomplete or irregular, the original boundaries between alteromorphs are no longer clear, and an area of several crypto-septo-alteromorphs is developed. These remarks apply to all kinds of septo-alteromorphs.

This kind of irregular septo-alteromorph is commonly developed at the expense of olivine and garnet and, in general, other uncleaved or poorly cleaved but fractured primary minerals, such as the feldspars.

Regular septo-alteromorph is developed where the septa are clearly oriented parallel to the cleavages of the primary mineral. Depending on the mineralogical composition of the primary mineral and its optical orientation with respect to the plane of the thin section, the septo-alteromorph may exhibit either a single network of parallel septa or a double network of crossing septa.

Pyroxene- and amphibole-group minerals and some types of feldspar commonly show a regular network of cleavages. This network is followed during the incipient stage of weathering, and is the starting point for the development of the later internal pattern of septo-alteromorphs. The network determines the density, distribution and orientation of the septa. Depending on the nature of the primary mineral and the orientation of its cleavages, regular septo-alteromorphs may be further subdivided into orthogonally (or nearly so) crossing networks (in the case of pyroxene-group minerals and alkali feldspar) and obliquely crossing networks (in the case of amphibole-group minerals).

Pyroxene- and amphibole-group minerals generally give rise to iron-rich septo-alteromorphs. If the original content of aluminum in the primary mineral is minor, the resulting alteromorph may be composed of aluminian goethite, in some cases associated with isolated small crystals of gibbsite. If isolated crystals of gibbsite appear, polyphase alteromorphs result. Iron-rich pyroxenes and amphiboles (hypersthene, augite, aegirine, hornblende, actinolite) give alteromorphs with thick septa and relatively small residual pores, whereas the more calcium- or magnesium-rich minerals (enstatite, diopside, tremolite, anthophyllite) usually give alteromorphs with thin septa and relatively larger residual pores (Delvigne 1965).

PART 3: ALTEROMORPHS

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The acantho-septo-alteromorph is a particular case of an alteromorph developed at the expense of twinned crystals. Grains of alkali feldspar and, more rarely, plagioclase develop septo-alteromorphs composed of gibbsite whose (possibly coarse) crystals are regularly organized along the cleavages. Coarsely twinned crystals of orthoclase can develop septo-alteromorphs characterized by two sets of septa, separated by the twin plane; each of these sets follows the cleavage planes particular to each individual original crystal. If each of them shows only one network of parallel cleavages, oblique with respect to the twin plane and with an orientation necessarily symmetrical with respect to it, a special kind of septo-alteromorph is developed with an internal "fish-bone" pattern (acanthomorphic pattern, from the Greek acanthos = fish bone). Grains of plagioclase more commonly produce irregular septo-alteromorphs by the combination of the networks of fractures with the numerous (polysynthetic) twin planes. Nevertheless, the "fish-bone" pattern can also be observed in the single-twinned (Carlsbad law) thin tabular crystals of plagioclase, common in ephitic and diabasic textures. Similar structures composed of iron oxyhydroxides may occur in acantho-septo-alteromorphs derived from the weathering of twinned crystals of pyroxene or amphibole.

If the feldspar is surrounded by a variety of minerals, the regular or irregular septo-alteromorph that develops can easily be identified in thin section. In contrast, if feldspar crystals are abundant in the parent rock, the resulting septo-alteromorphs may well be contiguous, with their individual outlines no longer clear or identifiable; they are then crypto-septo-alteromorphs or crypto-gloomo-septo-alteromorphs.

All adjacent grains in a given area may consist of a pyroxene or an amphibole. These may give rise to iron-rich alteromorphs whose secondary crystallites are all well oriented parallel to the Z axis of each grain of primary mineral. The boundaries between alteromorphs are expected to remain identifiable because under crossed polars, complete extinction or transmission of the different alteromorphs is not obtained simultaneously upon rotation of the microscope stage. The cryptomorphic pattern of the contiguous septo-alteromorphs appears clearly only under plane-polarized light, but it disappears if the polarizers are crossed.

**Complex "Poro"-Alteromorphs**

It is obvious that the textures observed within alteromorphs are rarely simple and perfectly developed. Numerous combinations of elementary textures can occur together within the alteromorphs. This complexity can arise in a serendipitous way, in which case it occurs only locally in the thin section. In this instance, the complex texture is accidental, and its description can be omitted. Complexity can also occur either commonly, under similar conditions of weathering independent of the nature of the primary minerals, or uniformly, in alteromorphs developed from the same parent mineral. In these cases, the complex patterns observed in the alteromorphs are characteristic, and a detailed description must be made. The most common cases of complex alteromorphs (Fig. 31) are described below.

Within a given alteromorph, the networks of cleavages and fractures together can influence the development and orientation of the septa. Within some septo-alteromorphs, large areas of regularly organized structure can be separated by one (or more) irregular septum. If the irregular septum is formed at the expense of a wide open fracture, it commonly appears as a complex curved or linear septum composed of two distinct parallel and relatively thick layers of crystallites separated by a planar and empty median pore. This pore corresponds to the opening of the fracture such as it appeared during the first stage of weathering. The more regular parts of the alteromorph correspond to the traces of the cleavages developed within the unfractured parts of the primary mineral. The resulting alteromorph is an irregular-regular-septo-alteromorph. This seems to be the simplest case of a complex alteromorph.

In alteromorphs developed from feldspars under conditions of ferrallitic weathering, the first-formed crystals of gibbsite regularly follow the networks of cleavages and fractures. They are arranged in banded textures of relatively constant thickness, which surround cavernous feldspathic residues. During a further stage of weathering, the progressive disappearance of these residues does not result in the thickening of the first-formed septa, but in the development of irregular aggregates of gibbsite crystals. The perinuclear pores, until now regular and of constant thickness, are converted into large irregular vughs. In the final stage of weathering, the alteromorph shows an intimate combination of two distinct microtextural patterns: thin septa, containing a double layer of well-oriented single crystals, constitute the elements of an embryonic septomorph texture whose development was interrupted in favor of volumes in which a gloomeromorphic texture is progressively developed. This last texture, located between the septa of the first generation, is composed of aggregates of randomly oriented crystals of gibbsite associated with large irregular pores, both
Figure 31. Definitions of alteromorphs on the basis of micro-textural criteria: the classification of complex alteromorphs. First example: the weathering of a feldspar-group mineral to gibbsite. Weathering occurs according to three basic patterns.
formed during the final stage of weathering. The complex alteromorph that shows the association and the interconnection of these two types of elementary textures is a *glomeroso-septo-alteromorph*.

The later evolution of some retiporo-alteromorphs, which are composed of a weatherable isotropic material, divided by a continuously reticular network of pores, can lead to the development of glomero-alteromorphs and septo-alteromorphs of a particular pattern. Indeed, each elementary polyhedral volume isolated by the reticular network of fissures can later be weathered to gibbsite. These crystals of gibbsite either define a concentric banded texture, owing to the peripheral and centripetal weathering of these volumes, or are arranged in irregular glomeromorphic textures, where weathering proceeds in a more disorderly fashion (Fig. 32).

In the first case, an *alveo-retiporo-alteromorph* is developed. It consists of a previously formed network of pores inherited from the retiporo-alteromorph, and a group of volumes all composed of a regular rim of gibbsite crystals surrounding a small residual pore. Each volume is converted into a small “centroporo-alteromorph”. Two generations of distinct organizations of pores are intimately associated. The first one consists of a single, open, continuous and reticular pore, whereas the second consists of many small, closed, discontinuous pores surrounded by a thin rim of gibbsite. Such rims consist of crystals of a similar size, arranged parallel to one another and perpendicular to the reticular network of pores. The organization of the crystals in the peripheral rims is similar to that observed in a septum. The only difference reflects the fact that the closed median plane observed in common septa is here replaced by an open median plane, which corresponds to one of the branches of the reticular network. This case is common in alteromorphs developed at the expense of nepheline and, in some instances, feldspar, where these minerals have weathered to gibbsite after an intermediate step involving further weatherable, easily shrunk and divided isotropic or amorphous material.

In the second case, a complex texture results whose different steps leading to their formation are recognized only with great difficulty. The reticular network of pores, which originated from the previous step, is well maintained during the later step. However, its boundaries are obscured or obliterated by the fact that the gibbsite crystals are no longer distributed as a regular rim around each solid polyhedral volume, as in the former example, but as aggregates of randomly oriented crystals exhibiting irregular boundaries and containing small isolated micropores. The irregular external porosity of these aggregates is, in this way, added to the regular pattern of the previously formed reticular pores. The resulting alteromorph is a *glomeroso-retiporo-alteromorph*.

An incorrect interpretation can result from the superficial observation of regular aggregates of small centroporo-alteromorphs developed by the simultaneous weathering of many small grains of a primary mineral that were organized, in the parent rock, into a mosaic-like, equigranular or granoblastic texture. The weathering can develop synchronously within all the constituents of the aggregate. It proceeds in a peripheral and centripetal manner from the intermineral suture planes. After the disappearance of the last primary residues and after the development of the residual pores, the compound structure, an assemblage of many minute centroporo-alteromorphs, may be very similar to an irregular coarse-grained septo-alteromorph. More detailed observation of such a texture generally shows that the fine dentoculation of the thin rims around the central alveolar pores exhibits various orientations. This observation provides proof of the different orientation of the original minerals and shows that the so-called septa are, in fact, only the traces of intermineral boundaries.

This case is common in some ultramafic rocks, in which small crystals of pyroxene, in a granoblastic texture, are weathered together to a smectite-group mineral or to iron oxyhydroxides concentrically arranged around small central pores. The weathered assemblage is not a septo-alteromorph, but rather an assemblage of small centroporo-alteromorphs, each individual component of which may exhibit its own specific orientation and extinction. The weathering of an assemblage of small grains of feldspar to gibbsite would be much more difficult to identify because the orientation of the gibbsite crystals is not inherited from the orientation of the primary feldspar; the secondary aggregate is a coalescent assemblage of crypto-alteromorphs.
COMPLEX ALTEROMORPHS

PRIMARY MINERAL

WEATHERING TO ISOTROPIC MATERIAL

RETIPORO-ALTEROMORPH

ABSOLUTE ACCUMULATION

EVOLUTION TO GIBBSITE

COMBINED PATTERNS

CUMULO-RETIPORO-ALTEROMORPH

META-ALVEO-RETIPORO-ALTEROMORPH

META-ALVEO-CUMULO-RETIPORO-ALTEROMORPH

**Figure 32.** Definitions of alteromorphs on the basis of microtextural criteria: the classification of complex alteromorphs. Second example: the weathering of nepheline to gibbsite via an isotropic intermediate phase (shown in yellow). Weathering may involve absolute accumulation or transformation to gibbsite, or both.
T he first photomicrograph, in XPL, shows the typical texture of a botryo-alteromorph in which small crystals of kaolinite are regularly distributed and randomly oriented. Each individual crystal is separated from its neighbors by isotropic material which, in this case, is the artificial material used for impregnation. Normally, in the uncut sample, the kaolinite crystals are nearly isolated from each other or stacked side by side, leaving between them small interstitial interconnected voids morphologically very similar to packing voids*. Most pores are interconnected and, as a result, the alteromorph is characterized by the occurrence of a single large pore in which individual crystals are regularly distributed.

The second photomicrograph, in PPL, shows a different kind of botryo-alteromorph in which small balls of radiating needles of goethite are closely stacked side by side in the empty pores of a septo-alteromorph after pyroxene. The balls are now visible only in a few parts of the alteromorph because most of the botryo-alteromorph has unfortunately been removed during the preparation of the thin section. The spaces between the septa are closed, which does not allow good penetration of the impregnating material. Thus most of the infilling material is not indurated, and is easily lost when cutting the rock.

* Redistribution of the kaolinite crystals occurs here.
TWO CONTIGUOUS grains of feldspar have been completely weathered to gibbsite. The original contact between them is marked by a discontinuous alignment of quartz of primary origin, and mainly by a major difference in orientation of the crystalliplasmas within each of the alteromorphs. The gibbsite crystals are arranged parallel to the cleavages of the original grains, which are oriented more or less perpendicular to each other. A septomorphic texture is not clearly observed. Large irregular vughs are distributed between the areas of crystalliplasma, whose components are tightly agglomerated in a manner typical of glomero-alteromorphs. Note that most elongate crystals of gibbsite are oriented parallel to each other. The thin section has been rotated on the microscope stage in such a way that most crystallites in the two alteromorphs can show their maximum interference-color in XPL. The absence or near-absence of septa is rarely encountered in an alteromorph after feldspar; transmineral fractures and internal cracks usually form many irregular septa of gibbsite, at least in the first steps of weathering. Where formed, these septa generally are preserved during the later steps, leading to glomero-septo-alteromorphs.
The hexahedral patterns shown in both photomicrographs are very similar and characteristic of the first steps in the ferralsitic weathering of plagioclase. The crystals are broken by irregular transmineral fractures and transverse cracks, along which weathering of the primary mineral has started. The first fissures are still recognizable as thin brownish lineaments that run in the median planes of the septa, reflecting a slight influx of iron. The most important septa originated from the fractures, but gradually, as weathering develops, more and more septa appear whose distribution and orientation are related to the cleavages of the primary mineral. The gibbsite crystallites are invariably oriented perpendicular to the median plane of the septa; their sizes and shapes are uniform along the septum, whatever its orientation. At the beginning of the weathering, very few or very small inter-plasma - mineral pores, if any, are developed, and the gibbsite crystals fill tightly against the cavernous residues of feldspar. Later, once weathering has progressed, irregular pores will develop at the expense of the residues, whereas the later-formed gibbsite produced will agglomerate, forming mixed glosamo-septo-alteromorphs.
Garnet-bearing mica schist
Yaounde area, Cameroon
Sampled by G. Stoops
Depth: unknown
Partially developed irregular septo-alteromorph (irregular linear weathering) after garnet
Objective: × 6.3
PPL and XPL

Garnet-group minerals of most metamorphic rocks are characterized by numerous irregular cracks whose reticular pattern divides the mineral into many contiguous fragments. These photomicrographs show a crystal of garnet that is highly fractured, with numerous radially distributed fractures, along which the weathering of the mineral has started according to an irregular linear pattern of weathering. Oxyhydroxides of iron form irregular septa whose thickness is hierarchized; thinner and thinner new septa are formed gradually as weathering proceeds, and the primary mineral is progressively reduced to smaller and smaller cavernous residues. These garnet residues are clearly seen as pink-colored remnants in PPL, whereas their isotropic nature makes them completely extinct in XPL. The septa are microcrystalline, and they are separated from the residues by irregular, colorless inter-plasma – mineral volumes partially filled, as shown by the picture in XPL, by crystals of secondary gibbsite. Gibbsite originates from the insoluble aluminum content of the primary garnet. Note that some thin septa grow parallel to each other (D2). This parallelism probably is a reflection of a particular feature, like twin planes in the garnet. When completely weathered, this alteromorph after garnet will be a typical irregular septo-alteromorph in which most septa are radially distributed. As the alteromorph contains at least two secondary phases, the oxyhydroxides of iron and gibbsite, it is considered a polyphase alteromorph (see later).
Whereas the feldspar minerals are weathered to gibbsite (308), the ferromagnesian minerals of the rock are weathered to iron oxyhydroxides. The distribution of the secondary products is here also determined by the irregular network of intramineral fractures, but it is mainly determined by the regular cleavages of the original mineral. The photomicrographs show the beginning of the weathering of a clinopyroxene to a regular network of parallel ferruginous septa whose distribution is closely related to the cleavages of the mineral. Whereas the feldspar minerals give cavernous residues, the ferromagnesian minerals give denticulate residues. Note that the denticulation is invariably oriented parallel for all the residues produced from the same grain. Note also that irregular pores quickly develop all around the residues. This difference in porosity resulting from the weathering of feldspar- and pyroxene-group minerals reflects the fact that the content of insoluble aluminum of calcic plagioclase is much greater than the content of insoluble iron of the original clinopyroxene. During the first step of weathering, all residues, tightly encased in the residual ferruginous network, maintain their simultaneous extinction in XPL. However, as soon as weathering is more advanced, the increased volumes of the pores allow this regular orientation to be partly disturbed.
**PART 3: ALTEROMORPHS**

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**CALC-ALKALINE GRANITE**
Blapleu, near Man, Western Côte d’Ivoire
Depth: 2.4 m

Regular septo-alteromorph after plagioclase
Objective: x 10 XPL

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315

**CALC-ALKALINE GRANITE**
BR 158, Brazil
Sampled by F. Soubies
Depth: 3.4 m

Regular septo-alteromorph after hornblende
Objective: x 10 PPL

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The first photomicrograph shows the last step in the weathering of plagioclase, whose regular parallel cleavages have determined the regular distribution and orientation of the residual septa of gibbsite. Traces of the first thin fissures generated during the first step of weathering along the cleavages are still recognizable in most septa by their dark color, which is related to influx of iron in the first open cleavages, before the formation of secondary gibbsite had started. Note the elongate residual pores randomly distributed within the septo-alteromorph. Such a case of regular distribution of septa is not common in alteromorphs after feldspar-group minerals.

The second photomicrograph shows a pseudomorph after a euhedral crystal of hornblende. The original crystal contained many inclusions of a chlorite-group mineral, which is now partially weathered to iron-stained kaolinite (yellow-colored irregular inclusions). The hornblende crystal, whose Z axis is oriented perpendicular to the plane of the thin section, shows a regular intersection of oblique iron-rich septa that originated from its weathering along cleavages, which are regularly oriented at 56° and 124°.
**AMPHIBOLITE**

Bereby, Southwestern Côte d'Ivoire

Sampled by A. Perraud

Depth: unknown

Regular septo-alteromorph after amphibole (actinolite)

Objective: x 6.3

PPL and XPL

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The photomicrographs show the typical pattern of the septa generated by the weathering of a crystal of actinolite conveniently oriented to show clearly the regularly intersecting ferruginous septa. One set of septa is oriented N-S in the photograph, whereas the second set crosses the first one at angles of 124° and 56°. The low iron content of the primary amphibole is responsible for the thinness of the ferruginous residual septa and for the high ratio of the pore volume relative to the volume of the residual secondary products. The photomicrograph taken in XPL shows the microcrystallinity of the iron oxyhydroxides that make up the residual septa; the photograph has been taken in a specific orientation of the microscope stage to clearly show that all the secondary crystallites are optically oriented in the same direction, their maximum interference colors are uniform, and, as a result, their extinction is simultaneous for all the crystallites of all the septa of the whole alteromorph. A photograph in which all crystallites are at extinction in XPL is not shown because the septa would not be clearly distinguished from the residual pore space. A convenient example with which to compare the simultaneously illuminated or extinct contiguous alteromorphs is given by the next illustrations. Small feldspar grains are weathered to gibbsite crystalliplasmas.
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CHARNOCKITE
Summit (1,000 m) of Tonkoui Mountain,
Western Côte d'Ivoire
Depth: 0.6 m
Regular septo-
alteromorph after amphibole
Objective: ×10
PPL and XPL

Photographs clearly show the influence of the crystallographic orientation of the primary mineral on the orientation of the microcrystalline secondary products. Where thin or incomplete septa of the right alteromorph are cut parallel to the plane of the thin section, they appear, in XPL, as bright yellow septa, which indicates that the main secondary constituent is goethite. Goethite is always preferentially formed in the place of hematite in alteromorphs in which the volume of the pores is high and in which, as a result, the circulation of water is easy, and the quantity of water available is great.
This micrograph shows another example of a mineral grain that is conveniently oriented to illustrate the regularity of distribution and the pattern of orientation of its residual septa. The septa intersect at an angle of approximately 90°, which allows the parent mineral of the alteromorph to be determined: it is not an amphibole, as in the previous illustrations, but a pyroxene. Whichever the original ferromagnesian mineral, the main textural and optical characteristics of the alteromorphs formed are very similar. In both cases, the septa-forming particles of goethite are strongly oriented according to a particular orientation of the primary mineral. The second photomicrograph, in XPL, clearly shows the regular orientation of these secondary particles, which allows all the septa of the alteromorph to be illuminated simultaneously. The plagioclase grains of the rock are now completely weathered to glomerosepto-alteromorphs of mesocrystalline gibbsite. Note that no gibbsite crystals are observed in the ferruginous alteromorph, and that the thin ferruginous threads observed in an alteromorph of gibbsite (A1, 2) are due to continuous transmineral fissures. Few crystals of gibbsite are observed along one edge of the ferruginous septoalteromorph (D3, 4). Their unusual occurrence there is probably due to the oblique orientation of the intermineral boundary in the plane of the thin section.
A TWINNED CRYSTAL of pyroxene has been weathered to goethite, giving rise to a double septo-alteromorph whose residual pores have been later infilled by crystallaria of allochthonous origin. The cleavages, and consequently the septa, of the two parts of the twinned crystal are symmetrically distributed, which gives rise to an “acantho-septo-alteromorph” ("fish-bone" pattern). The second illustration, in XPL, shows that both goethite-rich domains are equally illuminated when symmetrically disposed relatively to the cross-hairs of the microscope. The third illustration shows that with a different angle of rotation, all the septa of one part tend to be at extinction, whereas the other part is at its maximum illumination. As a result, these exceptional pictures obviously show that the orientation of the goethite particles is strongly influenced by the crystallographic orientation of the primary mineral. The orientation of the gibbsite crystals is random, and obviously independent of that of both primary and secondary minerals.
This photomicrograph illustrates the case of a complex septo-alteromorph whose orientation and regularity of the septa depend on the combined effects of the cleavage pattern of the primary mineral, together with several twin planes. The septa that develop from the twin planes are nearly parallel to the short edge of the photograph, whereas the septa developed from the cleavage planes are oriented oblique to these edges. The fact that two sets of septa are reciprocally oriented according to angles of nearly 120° and 60° indicates that the primary mineral was an amphibole-group mineral. The thinness of the septa indicates that the primary mineral was an iron-poor amphibole. Minute remnants of primary amphibole are still distinguishable within some residual pores (D4). Rounded and still unweathered inclusions of quartz are clearly seen within and around the septo-alteromorph.
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CHARNOCKITE
Summit (1 000 m) of Tonkoui Mountain,
Western Côte d'Ivoire
Depth: 0.6 m
Glomero-septo-
alteromorph
after feldspar
Objective: x 10
XPL

0.2
0.1
0.0 mm

327

GABBRO
Bondoukou area,
Eastern Côte d'Ivoire
Sampled at outcrop
Botryo-septo-
alteromorph
after feldspar
Objective: x 10
XPL

The first illustration shows a typical glomero-septo-
alteromorph, such as is commonly encountered in most alteromorphs
after feldspar-group minerals that have been modified under condi-
tions of ferrallitic weathering. The first-formed fissures and fractures
lead to the development of the septa, whereas during a later stage
of weathering, the remnants of feldspar are progressively replaced
by gibbsite, whose crystals are agglomerated in large portions
delimited by interconnected vughs. The gibbsite crystals of the septa are
commonly regularly oriented perpendicular to the ferruginous traces
of the fissures, whereas the agglomerated crystals of gibbsite are ran-
domly oriented.

The second illustration shows a much rarer case in which, after a
first step of septa development, as in the previous case, the feldspar
residues are replaced by isolated crystals or isolated small groups of
crystals. These are randomly ori-
ented and distributed in large vughs
whose shapes, volumes and position
are related to those of the remnants
of feldspar. All these gibbsite crys-
tals seem isolated in the plane of the
thin section but, in reality, they are
probably linked, in the third dimen-
sion, in the same way as skeleton
grain are stacked side by side in a
monic* texture.
Criteria for a Genetic Classification

Chapter 9

There is another level of complexity that can be added to the complexities presented by the microstructural organizations previously described. It results from the simultaneous occurrence, within a given alteromorph, of several distinct secondary mineral phases (Fig. 33). Alteromorphs in which several secondary minerals are simultaneously observed are composite alteromorphs.

Composite Alteromorphs

Composite alteromorphs consist of two or more associated secondary minerals, of hypogene or supergene origin (or one of each). The remnants of the primary minerals, temporarily maintained within the incompletely developed alteromorphs, are not taken into account in the definition of this kind of microtexture.

The composite character of these alteromorphs is independent of their external shape and their internal morphology. The pattern of orientation of one component relative to the other may be uneven, parallel, concentric or crossing. The pattern of distribution, within the alteromorph, may be uniform, clustered, peripheral, central, or otherwise. Composite alteromorphs may consist of polygenetic or polyphase assemblages.

Polygenetic alteromorphs

Polygenetic alteromorphs are formed in two or more successive stages, very commonly according to different processes of alteration of hypogene or supergene origin (or one of hypogene and one of supergene origin), widely separated in time. During the first stage, alteration (or weathering) has not transformed the primary mineral in its entirety. During the second stage, the remnants of the primary mineral are transformed to different secondary minerals without modification of either the mineralogical nature or the spatial distribution of the first-formed secondary product. The distribution of the first-formed mineral phase may be concentric, radial, parallel, crossing or random, whereas the second-formed mineral phase occupies the entire volume of the islands of residue (Fig. 34).

Some examples serve to illustrate the three most commonly encountered cases of composite alteromorphs (Fig. 35).

Case 1: two stages of hypogene alteration (Fig. 35A). During a first stage, crystals of olivine may be partly replaced by serpentine or talc. During a later stage, the remnants of olivine are altered to saponite or “iddingsite” without modification of the early-formed serpentine or talc. The reciprocal and complementary distribution of the two secondary minerals may be uneven, parallel or concentric.

Case 2: one stage of hypogene alteration followed by a second stage of supergene origin. During the first stage, grains of orthopyroxene are partly altered to talc by a hydrothermal process. Much later, in terms of geological time, the remnants of pyroxene are weathered to a smectite-group mineral without modification of the mineralogy or distribution of the first-formed areas of talc. A second example is given by the formation of “sericite” and zoisite inclusions by hydrothermal alteration of a crystal of plagioclase (Fig. 35B). During a later process, the remnants of feldspar are weathered to kaolinite without modification of the less weatherable inclusions.

Case 3: two stages of supergene reaction. Coarse crystals of orthopyroxene are weathered, in the lower parts of a profile, to a banded texture of smectite enclosing unweathered remnants of pyroxene. These will later, in the upper parts of the profile, be weathered in a peripheral and centripetal manner to iron oxyhydroxides, whereas
FIGURE 33. Definitions of alteromorphs: the establishment of criteria for a genetic classification of complex alteromorphs. Such an approach is necessary where two or more secondary minerals are observed together within the alteromorphs.
the smectitic component is temporarily maintained in the composite alteromorph. Another case of a composite alteromorph is given by the complete weathering of a pyroxene crystal to a septo-alteromorph of goethite, whose internal pores are later infilled by gibbsite crystals by absolute accumulation of allochthonous material.

In this latter case, the resulting composite alteromorph is more appropriately described as a cumulo-alteromorph (see below).

Inadequate observation of some polygenetic alteromorphs, where several secondary minerals are juxtaposed, can in some instances lead to erroneous interpretations (Fig. 35C) concerning their origin and the development of their alteration.

**EXAMPLE OF ERRONEOUS INTERPRETATION**

As a result of a deep-seated late-magmatic process, an originally homogeneous crystal of clinopyroxene may be partly transformed to many small inclusions of hornblende. These inclusions generally exhibit a common crystallographic orientation, inherited from or influenced by the crystallographic orientation of the host crystal. During the first stage of subsequent supergene weathering, the more weatherable pyroxene is weathered to a secondary smectite-group mineral whose sheets are well oriented parallel to the Z axis of the pyroxene crystal. The more resistant inclusions of hornblende are not yet weathered. As a result, they are now included in a secondary product with which they are neither genetically nor directly connected. These “residual” inclusions of amphibole are not the residues of the primary mineral from which the smectite formed. It is necessary to compare such alteromorphs with less developed ones, in which residual areas of pyroxene are still associated with the hornblende inclusions, to properly interpret the process of development of both secondary products (smectite and amphibole).

In contrast, some polygenetic alteromorphs provide, either by their mineral content or by their microstructure, an additional source of information, not only about their origin, but also about the primary minerals from which the alteromorphs developed. Thus, in a monzonite or calc-alkaline granite, all grains of feldspar may have been weathered to kaolinite; there is no possibility of clearly distinguishing the origin of the alteromorphs, either by their shape, their color, or internal microtexture. All these similar alteromorphs, with poorly identifiable boundaries because all have the same secondary constituents, are associated in such a way that they form a group of crypto-alteromorphs. More detailed and accurate observations may show that some alteromorphs contain inclusions of epidote, mainly in their central parts, whereas other alteromorphs do not. The first alteromorphs are probably developed from plagioclase, whereas the inclusion-free alteromorphs are probably developed from microcline or orthoclase.

Another example is given by crypto-alteromorphs simultaneously developed at the expense of adjacent crystals of olivine and orthopyroxene (Fig. 18C). Both alteromorphs have a smectitic composition, but the occurrence or the lack of a symplectic microstructure or of “iddingsite” will allow one to determine the primary mineral from which a given alteromorph has developed; olivine does not contain symplectite, but can show partial transformation to “iddingsite”, whereas orthopyroxene may contain symplectite, but never contains “iddingsite”. In some cases, the distinction between the two alteromorphs is more difficult where both types of alteromorphs, after olivine and orthopyroxene, are weathered to very similar smectite-group minerals (Fig. 18A). Only the difference in orientation allows one to distinguish their origin. Smectite particles after olivine are very small and randomly oriented, whereas smectite particles after orthopyroxene are larger and oriented parallel to the Z axis of the primary mineral.
FIGURE 35. EVOLUTION OF POLYGENETIC ALTEROMORPH.

A. Two different episodes of alteration of hypogene origin, separated in time
0: anhedral crystal of olivine exhibiting prototactic intraminal fractures;
1: incipient first stage of alteration of olivine to serpentine and magnetite along the fractures and rim;
2: advanced first stage of alteration; banded texture of serpentine and magnetite, with large relict cores of olivine;
3: incipient second stage of alteration of the relict cores to "iddingsite" without modification of the first-formed serpentine;
4: final stage of alteration; banded texture of serpentine and inner parts of "iddingsite"; POLYGENETIC ALTEROMORPH.

Note: The first-formed banded texture can be considered as a partly developed two-phase alteromorph since two secondary minerals (serpentine, magnetite) are formed together at the expense of the olivine. In this polygenic alteromorph, the first stage gives a two-phase alteromorph, and the second stage, a single-phase one.

B. One hypogene process of alteration followed by a supergene process
0: anhedral zoned crystal of plagioclase, with its characteristic pattern of polysynthetic twinning;
1: incipient first stage of alteration affecting the core, leading to minute crystals of clinozoisite;
2: more advanced stage of alteration and growth of the clinozoisite crystals, still with voluminous residues;
3: incipient weathering of the plagioclase to an isotropic material along boundaries and twin planes;
4: isotopic material replaces the feldspar without disturbing the inclusions; POLYGENETIC ALTEROMORPH.

Note: This polygenic alteromorph is susceptible to further modification; gibbsite may crystallize at the expense of the isotropic phase, and gibbsite and goethite, in porous assemblages, may form at the expense of the epidote inclusions. The polygenic and polyphase aspects of the complete alteromorph remain perfectly recognizable.

C. Example of possible erroneous interpretation of the genesis of an alteromorph
0: crystal of clinopyroxene showing parallel cleavages and transverse fractures;
1: incipient alteration of the pyroxene to hornblende along the cleavages and fractures;
2: the hypogene alteration ceases; dendritic and oriented inclusions of hornblende coexist within the unaltered pyroxene;
3: incipient weathering of the residual cores of pyroxene to oriented domains of a smectite without disturbance of the inclusions;
4: complete weathering of the pyroxene to smectite and undisturbed inclusions; POLYGENETIC ALTEROMORPH.

Note: All the inclusions of hornblende are optically oriented, and their coarsely dendritic shapes can simulate residues of the mineral that has given rise to the oriented smectite. In this example, hornblende is not the parent material of the secondary smectite. Without access to the less advanced stages, the identification of the true process provides a major challenge.
A partially and peripherally altered area has developed. The transformation has progressed centripetally, leaving a large core of undisturbed olivine. The serpentine is colorless in PPL, and exhibits, in XPL, its usual low interference-colors (first-order grey). The internal microtexture shows that the domains of serpentine are not preferentially oriented. During a later stage of alteration, a postmagmatic process has replaced part of the unaltered olivine core with “iddingsite” while maintaining the pattern of its network of protoclastic fractures, which had become obscured in the serpentinized area. The transformation of the olivine core is not complete, as many small residual fragments are still recognizable (colorless in PPL and blue under XPL) within the “iddingsitized” area. This transformation of the olivine core to “iddingsite” has obviously followed the inner protoclastic fractures, since all olivine remnants are well centered within each cell of “iddingsite”. Note that the second stage of transformation has not affected the early-formed serpentine mineral(s). Formed during two successive stages of transformation, with crystallization of two different secondary products, the complex alteromorph is a typical (nearly complete) polygenetic alteromorph.
With the preceding illustrations, these photomicrographs show the result of a very similar but somewhat more complex process of transformation of an olivine grain according to two successive stages. The additional complexity lies in the fact that the first stage of alteration gives rise to a partial polyphase alteromorph with two distinct secondary minerals. The alteration front penetrates the olivine crystal along transmineral fractures, and gives rise to serpentine-group minerals, with concomitant crystallization of magnetite, which lies along the median planes of the serpentinized bands. Magnetite contains the iron, originally included in the olivine crystal, that has not been accepted within the newly formed serpentine-group minerals. The olivine domains that have “escaped” the serpentinization process have been later completely replaced by “iddingsite” without affecting the first-formed serpentine-group minerals. During a later step of supergene weathering, some new transmineral fractures are opened, along which manganese oxides are deposited (see 048, 049, and 346). Note that the serpentine-group minerals are preferentially oriented perpendicular to the median plane of the fractures and to the intermineral boundary of the alteromorph, as can be seen under XPL.
Olivine-bearing clinopyroxenite
Koua Bocca, Côte d'Ivoire
Depth: 6.8 m
Polygenetic alteromorph after olivine
Objective: x 6.3
PPL and XPL

The photomicrographs illustrate the case of a very complex polygenetic alteromorph that results from the combined effects of several stages of transformation. A large grain of olivine was partially and peripherally replaced by a thick external rim of many randomly oriented crystals of orthopyroxene and by an intermediate thinner rim showing a symplectic texture surrounding the olivine core. During a later step of mild hydrothermal alteration, the olivine core has been completely replaced by well-oriented saponite (bright yellow in PPL and nearly at extinction in XPL), without modifying the peripheral grains of orthopyroxene. The network of original protoclastic fractures is still recognizable in the saponite core. During a later step of weathering, the orthopyroxene of the external rim was partially weathered to nontronite, but there are still many denticulate residues, whose orientations correspond to the mosaic-like assemblage of the primary orthopyroxene grains. The nontronite is easily distinguished from the saponite after olivine by its beige-brown color. The magnetite of the symplectic texture is not modified, and its occurrence and distribution allow the peridotitic parent of the polygenetic alteromorph to be identified.
These photographs illustrate a case of a polygenetic alteromorph whose ultimate origin is very similar to that in the previous example: the original mineral is also a grain of olivine, but it has completely disappeared, and is replaced by a mosaic-like assemblage of small, randomly oriented crystals of orthopyroxene (hypesthene). The grade of hydrothermal alteration is somewhat higher than in the former example, and part of the peripheral pyroxene has been replaced by randomly oriented and colorless particles of talc, clearly observed along the right and bottom edges of the photographs. During a later step of weathering, part of the orthopyroxene crystals, whose pink pleochroism is clearly exhibited by some of the residues, is now replaced by nontronite, whose greenish yellow color allows a distinction with the colorless rim of talc. Some linear traces of magnetite run across the alteromorph; they are the ultimate traces of the protoclastic fractures of the original crystal of olivine. Note that many small crystals of orthopyroxene have been completely weathered, and are replaced by many small centro-alveoporo-alteromorphs. The dark green inclusion (B2) is hornblende, and the dark grains that surround the polygenetic alteromorph are partly altered crystals of clinopyroxene.
These photomicrographs, taken from the same thin section as the previous ones, are included to better show the details of the distribution of nontronite and talc, and to better distinguish the colorless rim of talc associated with magnetite lineaments (both features resulting from the influence of a late-magmatic hydrothermal alteration) from the green nontronite, formed by more recent weathering of the hypersthene grains that had not previously been replaced by talc. Some minute denticulate remnants of hypersthene are still distinguishable at C4, whereas most of the other orthopyroxene grains have completely disappeared, giving rise to small centro-alveoporo-alteromorphs. Note that the talc particles of the rim are randomly oriented, whereas the smectite particles, whose denticulations are related to the denticulations of the consumed residues of pyroxene, are regularly oriented, in each alveoporo-alteromorph, according to the orientation of each original grain. No olivine remnants are preserved, and no areas of the symplectite texture are visible in the area photographed. Only a careful observation of the whole thin section and of neighboring samples will allow the ultimate origin (complex evolution of an olivine grain) of the polygenetic alteromorph to be identified.

PART 3: ALTEROMORPHS
During a first step of hypogene alteration, most of the olivine has been replaced by a banded texture involving serpentine-group minerals, maintaining large cores of primary olivine. The banded texture forms an irregular reticulate and interconnected network whose thickness is largely hierarchized. The longest bands of serpentine exhibit a greater thickness than the shortest ones, whereas the olivine residues all have a comparable volume. The serpentine-group minerals are pale yellow in PPL. The fact that the thin section is slightly thicker than usual makes the maximum interference-color of the secondary mineral first-order yellow instead of grey in XPL. The serpentine-group minerals are generally oriented perpendicular to the walls of the veinlets, whose median plane contains particles of magnetite. Magnetite and serpentine are formed together during the polyphase alteration of the primary olivine. During a later stage of supergene weathering, the olivine cores have been weathered to saponite, whose green coloration is attributed to its relatively high content of Ni. No olivine remnants are retained in the alteromorphs, and the orientation of the particles of saponite seems to be random. Slight influx of brownish oxyhydroxides of iron, probably due to partial oxidation of the magnetite, is observed within the banded texture of the serpentine veins.
A POLYGENIC NETWORK of serpentine veinlets (yellowish in PPL), formed during a first step of hypogene alteration, divides a large crystal of olivine into irregular residual fragments. During a later step of supergene weathering, the olivine remnants were first partially weathered to beige-brown saponite, which is irregularly distributed in the contact areas (A3) between olivine and serpentine. During a second stage, a weathering reaction affected the remnants of olivine following a constant orientation, which is related to the main crystallographic orientation of the original crystal, and gave rise to dark brown oxyhydroxides of iron. No open pores are visible between the primary remnants and the secondary products, at least at the scale observable with an optical microscope. Some elongate artificial pores (black holes in XPL) are defects of the thin section. Small patches of oxyhydroxides of iron are also irregularly distributed within the serpentine veins; they reflect an irregular influx of iron and not a true weathering of the serpentine-group minerals. These will be weathered much later and at a higher level in the profile. Formed under the influence of two different processes well separated in time, the resulting alteromorph, once the replacement of the olivine remnants is achieved, will be a typical polygenetic alteromorph.
A n-olivine phenocryst has been partially altered to “iddingsite” during a late diagenetic process. The “iddingsite” rim is brownish red in PPL, and brightly colored in shades of yellow and orange in XPL. During a later step of weathering, which is also responsible for the weathering of the basaltic groundmass, the olivine core has been completely weathered to hydrated oxides of iron which, in PPL, appear as a dark brown boxwork with numerous empty pores. Most of the septa appear, under XPL, as micro-aggregates of well-oriented domains of goethite, whose orientation is homogeneously distributed throughout the entire weathered core. The photomicrograph has been taken with the septa oriented at 45° to show the maximum brightness of the goethite particles; when oriented parallel (not shown) to the cross-hairs of the microscope, both “iddingsite” and goethite minerals appear completely at extinction under XPL. Both hypogene “iddingsite” and supergene goethite have inherited the textural orientation of the original grain of olivine. The result of the two-step transformation of the olivine grain is a polygenetic (oriented) septo-alteromorph.

The groundmass of the basaltic rock is completely weathered. The laths of plagioclase are transformed to nearly isotropic halloysite, and the interstitial grains of pyroxene have been replaced by oxyhydroxides of iron.
A weathered crystal of olivine has been replaced by a polygenetic alteromorph. During a first stage of hypogene alteration, a small part of the mineral has been replaced by yellow saponite (A–B5, D–E4), which has penetrated the mineral over short distances along the protoclastic fractures. During a later stage of weathering, under conditions of restricted drainage, the unaltered part of the olivine crystal has been completely weathered to greenish nontronite. The minute grains of magnetite lying within the protoclastic fractures remain undisturbed, and the previously formed saponite is not modified, texturally or mineralogically. Note that the microparticles of nontronite are randomly oriented over the whole alteromorph, as is usually observed in nearly all alteromorphs after olivine formed under conditions of restricted drainage in the Koua Bocca intrusion.
AN AMBULRAL GRAIN of olivine has been completely replaced by a holo-alteromorph of "iddingsite" under the influence of a later-magmatic process. Observations of the neighboring affected areas (beyond the thin section) indicate that the volumes of the primary mineral and of its alteromorph are similar, and that no deformation has taken place during this first transformation; an iso-alteromorph results. The position of extinction and the interference-colors under XPL (not shown) are homogeneous throughout the entire alteromorph, which indicates that the alteromorph is derived from one grain of olivine. During a later step of weathering, the weathered rock was crossed by many open transmineral fractures, and some of them have been the pathways along which absolute accumulations of allochthonous material have occurred. In the fractured alteromorph shown in the photomicrograph, the transmineral fracture is rimmed by an irregular halo of black manganese oxides, which also penetrated the alteromorph along thin internal fissures. Slight absolute accumulation of oxyhydroxides of iron is also responsible for the higher coloration of the "iddingsite" itself in sectors adjacent to the manganese-enriched areas. Owing to the influence of two successive stages of transformation (firstly, hypogene formation of "iddingsite", and later supergene absolute accumulations), the resulting alteromorph has become a (cumulo)-polygenetic alteromorph (see also 048, 049).
A first stage of hypogene alteration has completely replaced an olivine grain to a symplectitic intergrowth composed of orthopyroxene (hypersthene) and irregularly distributed vermicular magnetite. During a later stage of low-grade hydrothermal alteration, the surrounding crystals of phlogopite have been replaced by mesoalteromorphs of vermiculite, without modification of the neighboring grains of orthopyroxene and clinopyroxene. During a more recent stage of weathering, the very susceptible orthopyroxene has been transformed to a smectitic clay of nontronite composition, whereas the magnetite intergrowths were not modified. The persistence of such unweathered symplectitic intergrowths provides a true mineralogical and textural signature that allows the ultimate origin of the alteromorph to be recognized. Without the occurrence of these intergrowths, the alteromorph could be considered to result from the weathering of olivine (without passing through the orthopyroxene phase) or from the weathering of orthopyroxene (without recognizing its ultimate peridotitic origin). Note that contrary to the alteration of a similar symplectitic texture to talc (see 385, 386), this alteromorph exhibits residual alveolar pores, which reflect weathering with net loss of material.
The photomicrographs show another example of a grain of olivine that has been replaced by a symplectitic intergrowth of orthopyroxene and lamellae of magnetite. Contrary to the previous photographs, a large core of olivine has been maintained in the central part of the symplectitic intergrowth. Later, during a low-grade hydrothermal phase, the olivine core has been completely replaced by saponite (see 389, 390) without modification of the symplectitic texture or the chemical composition of the orthopyroxene rim. During a much later phase of weathering, the saponite core and the orthopyroxene-bearing rim have been strongly weathered to an alveolar texture of iron-rich secondary clays, whereas the magnetite intergrowths were oxidized to hematite. Its dark red coloration is clearly visible in the lower photograph, taken with crossed polarizers and condenser lens for an enhancement of the brightness of the nearly opaque secondary mineral. The oxidation of the magnetite to hematite has not modified the thin and brittle symplectitic texture which, as a true signature, remains perfectly recognizable even within the upper part of the iron duricrust. Without the persistence of this particularly characteristic texture, the identification of the ultimate origin of the complex polygenetic alteromorph would not have been possible.
THICK SOIL DEVELOPED ON OLIVINE-BEARING CLINOPYROXENITE
Koua Bocca, Cote d'Ivoire
Depth: 6.6 m

Polygenetic alteromorph
Example of a “signature”

Objective: × 10
PPL and XPL
Polarizers not exactly crossed in XPL

The microphotographs show a residual symplectitic texture, from which only the shape of the vermicular intergrowths has been preserved. The magnetite of the lamellae has been converted to hematite (dark red coloration in XPL, with full power), whereas the orthopyroxene component has been replaced by reddish alveoporo-alteromorphs of colored residual kaolinite, itself a product of degradation of previously formed nontronite (as it can be ascertained in the lower parts of the profile). The finely porous red alteromorphs that are distributed around the central polygenetic alteromorph are crypto-alteromorphs after grains of clinopyroxene, whose early-formed secondary products also have been replaced by ferruginous red kaolinite, similar in composition to the weathered orthopyroxene. The boundary between the orthopyroxene grains of the symplectitic texture and the surrounding weathered clinopyroxene grains is not clearly recognized because all the pyroxene grains have given rise to many irregular crypto-alteromorphs. Without the occurrence of this clearly recognizable symplectitic residual texture, the origin of this complex polygenetic alteromorph could not have been identified.
The upper illustration shows the myrmekite texture, which commonly develops in the contact area between plagioclase and alkali feldspar. The myrmekite texture is composed of vermicular inclusions of quartz within sodic plagioclase. The internal organization of the myrmekite texture is comparable to the previously shown symplectic texture. When subjected to weathering processes, the highly resistant inclusions of quartz may be maintained unweathered, like the magnetite intergrowths in previous examples, whereas the enclosing and neighboring feldspars are less resistant, like orthopyroxene, and may be completely weathered to clay minerals or even to gibbsite.

The lower illustration shows what happens in cases where a granophyric intergrowth of a sodic or a potassic feldspar with quartz has been subjected to conditions of efficient weathering. All the feldspar components, either in the granophyric intergrowth or in neighboring crystals, have been completely replaced by gibbsite. The resulting altermorphs are highly porous (mainly glomerol-altermorphs), but in spite of this high porosity, the original distribution and orientation of all the vermicular inclusions of quartz have been perfectly maintained, as shown by their homogeneous interference colors in XPL.
Polyphase alteromorphs:

Polyphase alteromorphs are formed during a single stage of hypogene alteration or of supergene weathering; they are thus monogenetic alteromorphs. On the other hand, the result consists of an association of two or more secondary minerals owing to exsolution (Fig. 36A) or to a gradual transformation (Fig. 36B), with development of an ephemeral intermediate phase. Slow rates of weathering of coarse crystals may also induce the development of two or more successive and distinct secondary phases, which will persist in the same alteromorph.

The neoformed products are not randomly distributed within the polyphase alteromorph, but they exhibit an organized, hierarchical texture. One of the two secondary products is invariably located close to the remnants of the primary mineral, whereas the other secondary phase is more distant, and separated from these remnants by the first one. Both hypogene and supergene processes can promote such polyphase alteromorphs.

Examples of polyphase alteromorphs of hypogene origin include the association of two neoformed minerals as a result of an exsolution process (Fig. 37).

The replacement of an olivine crystal by a symplectic intergrowth of orthopyroxene and magnetite corresponds quite well to the above definition. The resulting alteromorph is a two-phase iso-alteromorph, as no increase in volume is observed. In contrast, where a process of phase separation occurs, as in the replacement of an orthopyroxene crystal by an association of talc and magnetite microparticles, the original iron content of the pyroxene does not enter the structure of the talc, and magnetite crystallizes as independent microcrystals, commonly filling up the intermineral pores opened around it. A two-phase echino-alteromorph is developed (Fig. 37A).

This is also the case in the association of two secondary minerals, where the first-formed one is progressively replaced by the second through a gradual process related to slowly modified conditions of alteration.

An orthopyroxene crystal may be replaced by an alteromorph composed of several secondary products (polyphase alteromorph), whose proportions and distributions in the alteromorph are influenced by the local P-T conditions and by opportunities for ion exchange. Under conditions of low P and low T, talc (Tic) and magnetite (Mgt) are preferentially formed at the expense of the primary pyroxene (two-phase alteromorph). In contrast, under conditions of higher P and higher T, an amphibole (Amp) is formed at the expense of the talc, which is progressively less abundant, and finally disappears from the alteromorph. Two-phase (Tic + Mgt), three-phase (Tic + Amp + Mgt) and two-phase (Amp + Mgt) alteromorphs are successively developed at increasing P and T (Fig. 37B).

Two-phase alteromorphs may also develop under the influence of supergene processes. Either simultaneous formation of two different stable secondary minerals or the gradual replacement of a first-formed unstable secondary mineral by a later-developed more stable secondary product may be observed.

An example of a composite polyphase alteromorph of supergene origin illustrating the development of stable and separate secondary products follows.

The weathering of hornblende or of garnet, both relatively aluminoen, can lead to a septo-alteromorph whose septa are mainly composed of goethite or of aluminian goethite, whereas
A. Two concomitant but separate minerals developed during a process of gradual alteration
0: crystal of orthopyroxene with few cleavages and fractures;
1: incipient pellicular and linear alteration to talc associated with small amounts of magnetite;
2: more advanced alteration to talc and magnetite surrounding large residual cores;
3: talc fills the major part of the original volume, whereas magnetite invades the surrounding open intermineral fractures;
4: complete alteration to inner domain of talc and mainly external deposits of magnetite; TWO-PHASE ECHINO-ALTEROMORPH.

Note: If the original orthopyroxene does not contain iron, no magnetite is formed, but part of the talc can invade the surrounding intermineral fractures because the alteration is not strictly isovolumetric. It generates a small increase in volume as a result of opening and infilling of intermineral fractures. A (single-phase) echino-alteromorph develops.

B. Three secondary minerals (one is optional) developed during a process of gradual alteration
0: crystal of orthopyroxene completely replaced by an association of talc and magnetite (Fig. 8, A4);
1: incipient replacement of talc by small crystals of colorless magnesian amphibole;
2: more advanced stage of alteration: prisms of amphibole develop at the expense of the talc;
3: more and more protruding prisms of amphibole are formed, whereas the relative proportion of talc decreases;
4: nearly complete alteration to talc, magnetite and amphibole; POLYPHASE ECHINO-ALTEROMORPH.

Note: All these successive stages do not necessarily appear during the alteration of the same original mineral grain, as the relative development of each of these stages depends on the local intensity of the hydrothermal process.

C. Two secondary minerals appearing simultaneously under conditions of superficial weathering
0: crystal of hornblende exhibiting one set of cleavage planes and irregular fractures;
1: incipient linear and pellicular weathering to goethite along part of the open cleavages and boundaries;
2: more advanced weathering along cleavages and fractures, and development of circum-nodular residual voids;
3: few minute denticulate residues isolated within large residual voids, and development of crystals of secondary gibbsite;
4: septa of goethite coated with isolated crystals of gibbsite; TWO-PHASE SEPTO-ALTEROMORPH.

Note: Gibbsite crystals develop where the aluminum content of the original hornblende is not fully accommodated by the early formation of aluminum goethite; discrete gibbsite forms from the remaining part of the aluminum. Where the aluminum content of the amphibole is lower, aluminum goethite is formed only, and no crystals of gibbsite are visible in the alteromorph.
small crystals of gibbsite are randomly distributed along the sides of the septa, in the pores of the septo-alteromorph (Fig. 37C).

An example of a composite polyphase alteromorph of supergene origin, with development of an unstable (isotropic or not) intermediate phase, is provided by the gradual polyphase alteromorph (Fig. 38).

**The complex pattern of weathering of plagioclase**

A fractured grain of plagioclase (Pl) is weathered to a Si-Al-rich, optically isotropic material (IM), which is later transformed to kaolinite (Kin) (Fig. 38A). The most easily weathered part of the feldspar is either its more calcic central part, if it is normally zoned, or the parts located along the irregular network of its fractures. The weathered part shows an irregular outline owing to the combined occurrence of fractures, cleavage and twin planes, which locally accelerate the weathering in preferred directions. The plagioclase residues are tightly confined within the isotropic secondary phase, and exhibit cavernous volumes and an irregular outline. The isotropic material progressively grows at the expense of these residues, which finally disappear from the alteromorph. The weathering of the alteromorph formed at the expense of feldspar proceeds with increasing evolution of the chemical composition of the isotropic material (IM) and with appearance of the small crystals of kaolinite (Kin) within the first-formed, and thus within the chemically most evolved, isotropic areas. A complex organization of shapes and minerals results (polyphase alteromorph). At least three solid phases are associated during a given period of time in the same alteromorph (the feldspar residues, the intermediate isotropic phase, and the microcrystals of kaolinite). Unweathered inclusions of "sericite" or epidote also may occur if such inclusions were developed during an early stage of hypogene alteration (polygenetic alteromorph), and are now irregularly scattered within the three other phases. During the final stage of evolution, the complex organization is progressively simplified by the disappearance, firstly, of the feldspar residues, and secondly, of the intermediate isotropic phase. Finally, the feldspar crystal is completely replaced by an aggregate of kaolinite microcrystals in which "sericite" and epidote inclusions may be maintained. If the inclusions disappear without any discernible trace of secondary products, or if the original feldspar did not contain such inclusions, a monophase alteromorph results, composed of kaolinite only. The alteromorph is successively composed of (Pl + IM), (Pl + IM + Kin), (IM + Kin), and finally (Kin). If the inclusions of epidote (Ep) are later weathered to iron oxyhydroxides (oxFe), the successive alteromorphs consist of (Ep + IM), (Pl + IM + Kin + Ep), (IM + Kin + Ep), (Kin + Ep), and (Kin + oxFe). In this last case, the resulting alteromorph is polyphase, because it contains two distinct minerals, but it is finally turned into a monogenetic alteromorph because both secondary minerals (Kin and oxFe) were developed during the same long and continuous period of time, under conditions of superficial weathering.

Similar processes occur where grains of plagioclase are weathered to gibbsite through an intermediate isotropic phase (Fig. 38B). The weathering develops much more quickly than in the previous examples, in such a way that the first-formed crystals of gibbsite are aligned on both sides of the fractures, whereas they are separated from the residual cores of feldspar only by the thin rim of isotropic secondary material. This first distribution of gibbsite crystals gives rise to a partly developed septo-alteromorph. Within more evolved alteromorphs, the isotropic material extends inward to the center of each residual core, which finally disappears. The earlier-formed rims of isotropic material are now converted to irregular assemblages of gibbsite crystals. Where the replacements are complete, the polyphase alteromorph is converted to a monophase complex globero-septo-alteromorph.

Polyphase alteromorphs also may develop where weathering reactions proceed at a slow rate on relatively coarse crystals. A long period of time is necessary to complete the weathering of the grain. During this time interval, conditions of weathering can become progressively modified in such a way that the last-formed secondary products are no longer identical to the first-formed secondary products. A first partial weathering to a smectite-group mineral, for example, may be followed by a second stage of weathering of the residues to iron hydroxide. Although both secondary products are formed from the same mineral grain, the resulting alteromorph may be considered to be a composite alteromorph (Fig. 38C).
A. Appearance of a mineral after an intermediate isotropic phase (gradual process of weathering)
0: anhedral crystal of plagioclase exhibiting few regular cleavages and irregular transverse fractures;
1: secondary isotropic material develops according to a regular – irregular linear pattern;
2: regular – irregular banded pattern and continuous isotropic phase with cavernous residual cores;
3: all residues of the primary mineral have disappeared when the first booklets of kaolinite are formed;
4: more crystals of kaolinite develop at the expense of the isotropic phase. TWO-PHASE (GRADUAL) ALTEROMORPH.

Note: Under conditions of normal or restricted leaching, feldspar-group minerals are preferentially weathered to kaolinite after the development of an intermediate isotropic phase, which extends over most of the alteromorph before the appearance of the first-formed crystals of kaolinite. Kaolinite and residues of feldspar are rarely observed together in the alteromorph.

B. Appearance of a mineral after an intermediate isotropic phase (gradual weathering process)
0: anhedral crystal of plagioclase exhibiting few regular cleavages and irregular transverse fractures;
1: cracked patches of isotropic secondary material develop along part of the cleavages and fractures;
2: enclast. patches of isotropic material develop, leaving cavernous feldspar cores; the first crystals of gibbsite appear;
3: crystals of gibbsite develop according to linear and banded patterns, whereas minute residues of plagioclase still persist;
4: Part of the isotropic material is replaced by gibbsite and residual voids. GLOMERO-SEPTO ALTEROMORPH.

Note: Under conditions of strong leaching, crystals of gibbsite quickly develop at the expense of the most strongly leached (first-formed) parts of the intermediate isotropic phase, which may still contain residues of feldspar. Three phases are observed together before the alteromorph is completely developed. A two-phase alteromorph evolves into a single-phase alteromorph.

C. One continuously weathering phase under conditions of varying drainage
0: subhedral crystal of orthopyroxene with parallel cleavages and transverse fractures;
1: linear transverse pattern of weathering to a smectite under conditions of restricted drainage in the lower profile;
2: further development into a banded pattern along fractures and dessicate. cores oriented parallel to the cleavages;
3: in the upper part of the profile, conditions of efficient leaching promote the weathering of the residues to goethite;
4: goethite and residual voids replace the residues and smectite is slowly degraded. ALVEOPORO-ALTEROMORPH.

Note: Within the near-surface weathering horizons, in which conditions of drainage promote the destruction of the first-formed smectite and its replacement by iron oxyhydroxides, the first-formed ortho-alveoporo-alteromorph is slowly converted to a para-alveoporo-alteromorph, in which more rounded pores are developed, rather than the characteristic alveolar pores.
A euhedral crystal of olivine has been altered to green chlorite associated with many grains of secondary quartz and sparser grains of calcite under the influence of a postmagmatic process of hypogene origin. The shape, and probably the volume, of the euhedral crystal of olivine were perfectly maintained and are clearly recognizable. The alteromorph is a true pseudomorph. The three secondary minerals were formed together during the same process of alteration. The result of the transformation is a polyphase pseudomorph. All quartz grains apparently exhibit the same optical orientation throughout the pseudomorph, but this feature is not always observed in similar transformations of olivine crystals in other rocks or regions.
Polyphase alteromorphs

Transformed an olivine crystal into a polyphase alteromorph composed of greenish chlorite associated with quartz grains. Most quartz grains are concentrically distributed around a central part, which is mainly composed of chlorite associated with very small grains of magnetite. As can be seen under XPL, both quartz and chlorite are randomly oriented, without any specific relationship to the orientation of the original olivine. The deep blue interference-color of the chlorite is characteristic of the penninite variety of clinochlore. The surrounding matrix has maintained its usual basaltic composition, and contains plagioclase, clinopyroxene and magnetite.
The interstitial alteration of this subhedral crystal of relatively calcic plagioclase (labradorite) has given rise to an association of two distinct secondary minerals. Epidote and clinopyroxene, clearly distinguishable in XPL by their high interference-colors (common epidote) or by their abnormal blue and yellow interference-colors (clinopyroxene), are concentrically distributed as a rim in contact with the other neighboring minerals (hornblende, magnetite and greenish chlorite). The core of the plagioclase crystal has been mainly replaced by many minute flakes of paragonite. A few small grains of epidote also appear in the central part of the alteromorph. The original calcium content of the plagioclase grain has promoted the formation of the epidote-group minerals, whereas its sodium content has promoted the formation of paragonite. The low original content of potassium is responsible for the presence of minor "sericite", which is intimately associated with the paragonite. The redistribution of the main chemical constituents of the original mineral into two distinct secondary mineral phases has led to the formation of a typical polyphase alteromorph, whose mineral components exhibit a concentric pattern of distribution.
A fragment of hypersthene has been completely altered to a regularly distributed association of talc and tremolite. As observed in XPL, all the blue-colored acicular domains of tremolite are regularly distributed parallel to each other and irregularly embedded in a groundmass of unoriented microparticles of talc. It is highly probable that in the third dimension, all isolated domains of amphibole are joined by bridges forming a skeletal mineral whose interstitial volumes are infilled by talc. Several generations of magnetite can be distinguished. The oldest is expressed as irregular opaque lineaments (C4, D3) that are related to the protoclastic fractures of the primary crystalline olivine before its later recrystallization into hypersthene. The second generation of magnetite is expressed as a group of irregular inclusions (A1, B2), which are relics of a symplectic texture formed as a result of the replacement of olivine by the newly formed orthopyroxene. The third generation is expressed as interlamellar parallel lineaments that have formed during the later replacement of the pyroxene by talc and tremolite. Observations of many thin sections showing the successive mineralogical transformations are necessary to understand such a complicated evolution.
Many amphibole crystals are twinned, but their regular orientation throughout the entire alteromorph is responsible for a homogeneous coloration under crossed polars. The magnetite grains, which contain the original iron content of the primary orthopyroxene, are randomly distributed. Most magnetite grains are euhedral or subhedral (cubic or hexagonal sections). Transverse fractures are also responsible for alignments of small grains of magnetite and linear infillings of opaque minerals. Several elliptical grains of greenish brown hornblende are randomly enclosed within the polyphase alteromorph; their formation precedes the alteration of the orthopyroxene host crystal, and they do not belong to the minerals that compose the polyphase alteromorph. More resistant to hydrothermal processes, the inclusions of primary hornblende are not replaced by the secondary tremolite–actinolite amphibole.
A polycrystalline alteration after olivine has been formed by hydrothermal alteration along a transmineral fracture. Owing to the low grade of hydrothermal alteration, the distribution of the secondary products is not uneven; it strongly depends on the distance that separates a point from the fracture along which the hydrothermal fluids penetrate the mineral. Most of the alteromorph is composed of talc, associated with minute grains of magnetite. At short distances along both sides of the fracture plane, where higher-temperature conditions were reached, the olivine was replaced by colorless tremolitic amphibole. In the thin section from which these photomicrographs were taken, all olivine crystals are altered to talc, and the amphibole only appears within the alteromorphs that are crossed by the fractures. This case provides a good example of a polyphase alteromorph in which the linear distribution of the secondary products is related to the varying intensity of the alteration process. The iron content of the original olivine does not enter the structure of the talc, nor that of the tremolite. It is concentrated into a separate phase, the secondary magnetite. The grains of clinopyroxene that are crossed by the fractures are partially altered to greenish actinolite.
A single crystal of olivine has been completely replaced by a polyphase alteromorph containing tremolitic amphibole and magnetite. Both minerals were formed together under the influence of a hydrothermal process, whose intensity is greater than in the former example. This is the reason for the absence of talc in the alteromorph. Most of the magnetite crystals, which contain the iron content of the original crystal of olivine, are concentrated in a rim and in interstitial irregular areas between the crystals of tremolite. Magnetite also is concentrated in lineaments that are the protoclastic fractures of the original crystal of olivine. The traces of these fractures, which are commonly emphasized by resistant deposits of magnetite, are very characteristic features that allow one to easily distinguish the alteromorphs after olivine from the alteromorphs after orthopyroxene. In the latter case, prismatic crystals of amphibole are generally oriented parallel to the Z crystallographic axis of the pyroxene (see 361, 362, 363, and 364).
A.

A.

OLIVINE-BEARING CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 10.2 m
Random distribution in a polyphase alteromorph after olivine
Objective: x 6.3
PPL and XPL

288

ATLAS OF MICROMORPHOLOGY OF MINERAL ALTERATION AND WEATHERING
POLYPHASE ALTEROMORPHS

371, 372

BASALTIC ROCK
Ocean floor.
Costa Rica Rift
Leg 70, site S04b
Sampled by C. Laverne

Random distribution in
a polyphase alteromorph
after olivine

Objective: × 10
PPL and XPL

Note that the neighboring minerals, such as plagioclase and skeletal crystals of pyroxene, were apparently not altered during this process.

Under the influence of a post-
magmatic process, an olivine crystal has been completely altered to a polyphase alteromorph of chlore (pale green in PPL, extinct in XPL) in which fibrous crystals of actinolite (amphibole) are randomly distributed and randomly oriented.
The olivine (holoalteromorph) has been completely weathered to nontronite associated with hydrated oxides of iron along its intramineral protoclastic fractures. As in earlier photomicrographs, the secondary products fill the whole volume of the original grain of olivine (holoalteromorph), without appearance of intramineral residual pores (at least at the scale observable with the optical microscope). Note that the network of original protoclastic fractures is clearly recognizable in the alteromorph, but that the original deposits of magnetite are now oxidized to brownish secondary products. The apparently variable thickness of these products is due to variations of the orientation of the fractures with respect to the plane of the thin section. Note also that along these ferruginous lineaments, the nontronite particles are strongly oriented perpendicular to the plane of the original fractures, which clearly contrasts with the unoriented pattern of the inner parts. The thickness of these oriented banded textures is essentially constant throughout the alteromorph. Both nontronitic and ferruginous secondary products originated under the influence of the same supergene process of weathering; the transformation consequently results in a polyphase holo-alteromorph. The other components of the rock, clinopyroxene, hornblende and magnetite, are very slightly weathered, if at all.
375, 376

HORNBLENDE-BEARING
CLINOPYROXENITE
Koua Bocca, Côte d'Ivoire
Depth: 0.2 m

Polyphase alteromorph after hornblende
Objective: x 10
PPL and XPL
Polarizers not exactly crossed in XPL

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A portion of a hornblende whose Z axis is parallel to the plane of the thin section is partially weathered into a complex septo-alteromorph. The observed pattern is determined by the combination of the poorly developed network of parallel cleavages with several transverse cracks. Many denticulate remnants are still visible in the alteromorph; they are surrounded by large residual empty pores (peripheral voids or inter-plasma - mineral voids). Note that, as usually observed in alteromorphs after ferromagnesian minerals, the denticulation is mainly developed according to a direction parallel to the Z axis of the crystal. Weathered in an environment of efficient leaching in a soil horizon near the surface, the hornblende crystal gives two distinct mineral phases that concentrate the more insoluble elements: the high iron content of the primary mineral goes to form most of the septa, whereas its lower content of aluminum is expressed by individual minute crystals of gibbsite that preferentially grew on either side of the septa. These crystals are clearly seen in the second photomicrograph, taken with the polarizers crossed at 85° to better distinguish the empty pores from the deep brown septa. A more detailed observation of the gibbsite crystals and of the denticulate remnants shows that most of them are partly covered by the most recent generation of iron hydroxide.
A large portion of orthopyroxene has been completely weathered as a result of two successive stages of weathering. The first, under conditions of restricted drainage, has promoted the formation of thick bands of a smectitic secondary product developed along two trans-mineral fractures, between which large residual remnants were retained. These residues are denticulate and tightly enclosed, without any residual pores. Partly weathered, relatively coarse grains of pyroxene can be maintained for a long time, until a lowering of the soil surface by superficial erosion transfers, in a relative way, the material to the upper part of the profile. The conditions of leaching are gradually modified in such a way that they do not promote the further formation of a smectitic secondary product, as in the lower horizon. Instead, oxyhydroxides of iron and large residual empty pores form. This second stage of weathering starts peripherally around the residual remnants and along the parallel cleavage planes of the pyroxene, which determines the formation of numerous parallel brown septa. The first-formed smectitic product is not weathered, because it has not been destabilized. These two photographs can be compared with 141 and 142, taken 60 cm lower in the same profile, in which pyroxene remnants are just beginning to weather to oxyhydroxides of iron.
Orthopyroxene-bearing clinopyroxenite
Koua Bocca, Côte d'Ivoire
Depth: 1.4 m
Polyphase alteromorphs after hypersthene
Objective: × 6.3
PPL and XPL

When erosion rapidly lowers the soil surface, residues of weatherable minerals can be brought into the new geochemical environment, such that incipient weathering to smectitic secondary products is bypassed. Weathering thus gives rise directly to oxyhydroxides of iron. The photomicrographs show several crystals of orthopyroxene that have been partially weathered, in the lower level of the profile, to a smectite according to irregular banded patterns. Many relatively coarse islands of the primary mineral remain, each with denticulate margins. Once subjected to the new geochemical conditions, the denticulate cores have been quickly dissolved, giving rise to numerous large empty residual pores, internally rimmed by thin iron oxide deposits of relative accumulation. The denticulate shapes are well preserved, and their orientations within the neighboring alteromorphs still allow the crystallographic directions of the primary minerals to be clearly deduced. The weathering process results in the development of very porous alveo-poro-alteromorphs. Note that the early-formed smectite is barely weathered (or not at all) under these new geochemical conditions. The particles of smectite in most banded textures have maintained their own orientation, which they acquired during the first stage of weathering.
UP TO THIS POINT, in this section, the photomicrographs have illustrated the formation of two or more secondary products, which have differentially concentrated the chemical elements of the primary mineral. In these illustrations, two secondary products also occur together, but the development of the second one depends on the later evolution of the first-formed product; the polyphase alteromorph is due to a gradual transformation, with development of an ephemeral intermediate phase. A coarse lath-shaped crystal of plagioclase is partly encased within the unweathered rock (B4), and partly protrudes into the weathered crust (D2). During a first stage, weathering has given rise to a wide band of isotropic material, whose intermediate composition is gradually modified with aging. This material then is replaced by coarse-grained gibbsite, whereas the adjacent area now contains the isotropic intermediate product formed at the expense of the residual plagioclase. Gradually, as weathering progresses, the internal porosity of the rock and the local conditions of leaching are modified; the feldspar residue is then directly weathered to fine-grained gibbsite without passing through the ephemeral isotropic phase. From B4 to D2, unweathered feldspar, fine-grained gibbsite (of direct generation), isotropic intermediate phase, and coarse-grained gibbsite (early-formed from the isotropic phase) are successively encountered.
383, 384
Nepheline-bearing syenite (Lujavrite)
Poços de Caldas,
MG, Brazil
Depth: 0.5 m
Polyphase alteromorph after nepheline
Objective: × 4
PPL and XPL

A relatively coarse aspect of nepheline is first partially weathered to an isotropic intermediate phase according to a peripheral, centripetal process. This first stage gives rise to an irregular core surrounded by a colorless phase which, with aging, takes on a typical hierarchized retiporo-alteromorphic pattern (see also 300, 301 and 302). Further away from the core are the polyhedral volumes of isotropic material. They are smaller, and the reticular network of fissures is more closely spaced. The conditions of leaching are progressively intensified, and the open reticular network of the external concentric part is then invaded by fine lineaments of microcrystalline gibbsite, whose distribution is strongly related to the previously formed network. The allochthonous gibbsite first forms many small linked rings, which isolate small residues of the isotropic material. With aging, these isolated volumes progressively lose their residual silica, and are ultimately replaced by internal crystallaria of autochthonous gibbsite. From the center to the edges of the photograph in XPL, a residual core of nepheline, a thick rim of homogeneous isotropic material, ring-shaped allochthonous accumulations of gibbsite around isotropic residues, and mixed generations of gibbsite are successively observed. The small inclusions of rinkite (mosandrite?) and aegirine are not yet weathered; they are clearly observed in both photomicrographs.
Complex polygenetic-polyphase alteromorphs

Clinopyroxenite
Koua Bocca, Côte d'Ivoire
Depth: 4.2 m

Complex polygenetic-polyphase alteromorph after olivine and orthopyroxene

Objective: × 4
PPL and XPL

A complex polygenetic-polyphase alteromorph has been replaced, under late-magmatic conditions, by a symplectitic intergrowth of orthopyroxene and irregularly distributed grains of magnetite. No olivine remnants persist in the alteromorph. This first alteromorph is a normal polyphase alteromorph. During a later stage of hydrothermal alteration, the orthopyroxene part of the symplectite has been converted to talc, whereas the symplectitic texture is not disturbed and remains clearly recognizable in many parts of the alteromorphs. These examples of the symplectitic texture in which one component (magnetite) is not easily weathered are very useful in the recognition of the ultimate origin of many transformed rocks; they are equivalent to true mineralogical signatures. The final alteromorph is a polygenetic alteromorph because it formed in two steps well separated in time. The two mineral components that now make up the alteromorph do not belong to the same stage of alteration. Only the first stage is responsible for the polyphase character of the alteromorph. The particles of talc are randomly oriented; they are rather colorless in PPL, and exhibit high interference-colors in XPL. Small crystals of apatite are visible in the surrounding rock (A5, C1), which is, in the area photographed, mainly composed of large crystals of yellow vermiculite.
The first-formed polyphase alteromorph is similar to that shown in the two previous photomicrographs: an olivine crystal has been completely replaced by a symplectic intergrowth of orthopyroxene and magnetite, but the magnetite intergrowths are preferentially concentrated in the central part of the alteromorph. The second stage of transformation takes place under the very late influence of a supergene process that has weathered the orthopyroxene portion of the alteromorph to a smectitic secondary product. This beige-yellow product is regularly distributed around the core, which is composed of magnetite intergrowths, between which small areas of the smectite also are visible. The orthopyroxene portion has entirely disappeared.

With progressively more advanced weathering, the secondary smectite-group mineral undergoes an incipient degradation to oxyhydroxides of iron, which make the rim of the alteromorph slightly brownish. Two main stages of transformation (one hypogene and the other supergene) make this a polygenetic alteromorph, but each of these stages has promoted the formation of two secondary minerals (orthopyroxene + magnetite in the first instance, and smectite + oxyhydroxides of iron in the second). This sequence results in the formation of a double polyphase-polygenetic alteromorph.
Here is another example of an olivine crystal that has been replaced by a symplectic intergrowth of orthopyroxene and magnetite. In this case, a large part of the original crystal of olivine has survived in the central part of the polyphase alteromorph. Small areas of symplectite are easily identified, and form a partial rim between the bright yellow core and the thick beige-colored rim. After this first stage of transformation, the alteromorph contained a core of primary olivine and a rim of orthopyroxene + magnetite. During a second stage of low-grade hypogene alteration, the olivine core is completely replaced by bright yellow, regularly oriented saponite; the reaction has not disturbed the thin intergrowths of magnetite. The thick rim of previously formed orthopyroxene is still unaltered. During a much later step of shallow weathering (the third stage of transformation), the orthopyroxene part of the first-formed polyphase alteromorph is weathered to a beige-brown smectitic clay, whereas the saponite formed at the expense of olivine, in closer geochemical equilibrium with the supergene conditions, is not affected. Some residues of orthopyroxene are still distinguishable (A4, C2, C5) in the weathered rim. These successive stages of transformation result in a particularly complex polygenetic-polyphase alteromorph.
During a first stage of alteration, under the influence of a late-magmatic process, a crystal of olivine is partially replaced by a rim of orthopyroxene that extends all around the crystal, and by an intermediate ring of symplectite that irregularly surrounds the olivine core. During a later stage of hydrothermal alteration, part of the olivine core was first replaced by yellowish saponite, both along its network of protoclastic fractures (C4, E1) and as irregular patches (A3) in the contact area between the olivine core and the orthopyroxene rim. Later, the residual olivine of the core was largely replaced by reddish brown “iddingsite”, whose formation mainly started along the previously formed bands of saponite, leaving many remnants of olivine. During the latest stage of transformation, under the influence of shallow weathering, these residues of olivine have been weathered to orange-colored nontronite (B2, B4), whereas most of the orthopyroxene in the previously formed rim and in a large inclusion are now weathered to a pale yellow smectitic product (D2, C5). Some small dentilicate residues of orthopyroxene are still distinguishable. The unweathered grains that surround the complex alteromorph consist of clinopyroxene, which is much less weatherable.
A crystal of orthopyroxene (hypersthene) has been partially replaced by talc, during a first stage of hydrothermal alteration. The talc is peripherally distributed around a large residual core of orthopyroxene. A thin rim of magnetite (opaque) is developed, as usually observed in similar cases, around the talc alteromorph, which results in the formation of a first partially developed polyphase alteromorph. The magnetite rim concentrates most of the iron of the original pyroxene that cannot be accommodated in the structure of the neoformed talc. During a later stage of weathering, the residual core of hypersthene was weathered directly to a dark brown, iron-rich septo-alteromorph whose empty pores, clearly visible in the central part of the alteromorph, are regularly oriented parallel to the Z axis of the primary mineral. Irregular halos of oxyhydroxides of iron appear as a stain on the inner part of the previously formed talc around the central septo-alteromorph. Brown-colored secondary ferriferous products also are visible within the thick rim of talc; they are either diffusion halos from the surrounding weathered rock (or perhaps from the incipient weathering of the thin rim of magnetite), but they are not derived from the weathering of the talc, because it does not contain a significant amount of iron. The unusual yellow color of the talc is due to slight permeation by an iron-bearing solution through the peripheral part of the alteromorph. Produced under the influence of two processes that are well separated in time (the first one of hypogene origin, the second one of supergene origin), the two-stage alteration results in the formation of a polygenetic alteromorph. The occurrence of two secondary minerals (talc and magnetite) within the first-formed partial alteromorph makes the final alteromorph a complex polygenetic and partially polyphase alteromorph.
A part of orthopyroxene (hypersthene) has been partially transformed, under hydrothermal conditions, to tremolite (E1) and talc (D2). Both secondary minerals are associated with secondary magnetite, which expresses the portion of the original iron content of the orthopyroxene crystal that did not enter the structure of the hydrothermal silicate minerals. The magnetite grains are relatively coarse in the tremolite-bearing part of the alteromorph, and microgranular in the talc-bearing part. This altered part of the primary mineral is a polyphase alteromorph. Most of the orthopyroxene crystal has not been modified in this first stage of alteration. During a later stage of weathering, it was nearly completely weathered to yellowish saponite, which surrounds minute denticulate residues. As the geochemical conditions of the weathering became progressively modified, empty peripheral pores (black rims in XPL) were formed around the residues. These residues became free to rotate within the empty pores, and consequently lost their simultaneous extinction under crossed polars. More recently, part of the smectitic product was weathered to a brownish clay along an irregular transmineral fracture. The neighboring grains of clinopyroxene also are weathered, whereas the less weatherable hornblende is fractured only.
During a first episode of hypogene alteration, part of the olivine in the rock was serpen

tinized. The serpentine is distributed according to an irregular cross-banded pattern that surrounds many irregular cores of olivine. The photomicrographs show the successive transformations occurring in a single grain of olivine. During a later step of low-grade hydrothermal alteration, part of the olivine cores has been peripherally and centripetally altered to saponite. The sawtooth shapes that are rather characteristic of the saponite domains are still clearly distinguished even in this complex alteromorph. During a later step of supergene weathering, all the saponite rims have been replaced by deposits of iron oxide, mainly in the concentric areas in contact with the network of serpentine bands, whereas the olivine cores have been completely dissolved. The residual empty pores have been later infilled by secondary quartz, which also fills the open spaces created by the weathering of the saponite. The serpentine-group minerals have been little affected during all these successive stages of alteration. They acquired a yellowish color owing to permeation of iron-bearing solutions. With increasing degree of silicification, true silcretes will be formed in the upper part of the profile, and even the serpentine-group minerals will be replaced by a banded network of secondary quartz.
The presentation of these two photomicrographs, taken of an unaltered rock, is necessary to explain the development of the polygenetic alteromorphs to be shown in the next photomicrographs. The main crystal shown in these first two photomicrographs is a large grain of diopside. It included, during its growth, some grains of orthopyroxene, small remnants of which (irregular pale pink grains at C2,3) are still recognizable in the central part of the clinopyroxene crystal. Many irregular patches of brown amphibole and inclusions of magnetite also are embedded in the main crystal. The groundmass of the rock exhibits the usual mineralogical composition of most samples of clinopyroxenite from the Koua Bocca intrusion. Note that the large grain of clinopyroxene is composed of a single untwinned crystal, and that nearly all the amphibole inclusions exhibit the same crystallographic orientation throughout the host crystal. The weathering of a very similar complex crystal will be shown in the next photomicrographs.
A clinopyroxene is partly weathered to saponite as a secondary product. Its optical orientation is parallel to the Z axis of the primary mineral. Many small denticulate residues are still recognizable. Since the host pyroxene has a monoclinic symmetry, its extinction angle is very different from that of the secondary product. The photograph taken in XPL clearly shows this difference in orientation when the microscope stage is rotated in a direction such that only the secondary product is visible and the clinopyroxene remnants are all at extinction. Careful observation in PPL shows that inclusions of green amphibole are associated with the remnants of clinopyroxene, and that they are not weathered nor denticulate, because this mineral is much less weatherable than the clinopyroxene. The amphibole inclusions are not at extinction in the lower photograph. Once completely weathered, the pyroxene remnants will disappear in favor of more of the smectitic secondary product, whereas the amphibole inclusions will remain unweathered. An inaccurate observation of such a complex alteromorph can lead to an erroneous interpretation about the origin of the alteromorph. The amphibole inclusions are not the primary material from which the secondary products have formed. It is thus necessary to investigate other alteromorphs in the sequence in order to find remnants of the true precursor mineral.
The three photomicrographs show the case of a more advanced stage of weathering which, during an earlier stage, was very similar to the case shown in 400 and 401. The alteromorph after clinopyroxene is nearly complete; the saponitic secondary product, which exhibits a phylloporo-alteromorphic pattern, is well developed at the expense of a clinopyroxene crystal whose remnants have nearly completely disappeared. Most visible inclusions consist of unweathered amphibole well enclosed in the phylloporo-alteromorph. Only two very small remnants of clinopyroxene remain. They are visible only in the third photograph, taken at such an angle of rotation of the microscope stage that all secondary products are at extinction. They are recognizable by their higher interference-colors (very small blue-colored domains at C3, C5), contrasting with the lower interference-colors of the amphibole inclusions. Without the occurrence of these sparse remnants of clinopyroxene, the alteromorph would, as a result of a superficial observation of the first photomicrograph, possibly have been interpreted as resulting from the weathering of an amphibole crystal. Both photomicrographs taken in XPL show the perfect orientation of the sheet silicates throughout the entire alteromorph, according to the Z axis of the precursor mineral.
Cumulo-alteromorphs (from the Latin *cumulare* = to accumulate) are polygenetic alteromorphs developed by the late accumulation of allochthonous material within previously formed porous alteromorphs. The allochthonous material may result from the crystallization of minerals incorporating elements transported in solution, or from the deposition of material transported as small detrital particles (Fig. 39).

For example, the presence of tetrahedrally coordinated aluminum in nontronite developed from the weathering of olivine (a mineral devoid of aluminum) provides a good example of an imported allochthonous element that is incorporated in a secondary mineral of autochthonous origin. Aluminum also may contribute to the formation of gibbsite crystals in a koilo-alteromorph at the expense of quartz. Although the Al is external to the mineral with which it is associated, the gibbsite infills dissolution-induced pores in the quartz. In this last case, the accumulation of allochthonous material is easily distinguished by optical microscopy, whereas in the case of nontronite after olivine, the distinction will be recognizable only in light of results of detailed and accurate chemical analyses.

As an example of absolute accumulation over short distances, evidence for which arises by mass-balance arguments, consider the first step of weathering of anorthite (Merino *et al.* 1993):

**Aluminum Migration During the Weathering of Feldspar Grains**

The incipient isovolumetric weathering of feldspar into septa of gibbsite, along the first-formed fractures, generally does not generate appreciable amounts of pore space. Along the septa, crystals of gibbsite are closely and tightly distributed against the feldspar remnants, without development of visible inter-plasma — mineral pores. To replace a given volume of anorthite by approximately the same volume of gibbsite, some aluminum must be added to the weathering feldspar. According to the reaction: 

$$\text{CaAl}_2\text{Si}_2\text{O}_8 + \text{Al}^{3+} + 5 \text{H}_2\text{O} = 3 \text{Al(OH)}_3 + \text{Ca}^{2+} + 2 \text{SiO}_2 + \text{H}^+,$$

an important part of the aluminum necessary for the formation of the gibbsite must be imported from adjacent weathering grains of feldspar, whose porosity consequently is much increased. In the case of the weathering of albite to gibbsite, according to the reaction: 

$$\text{NaAlSi}_3\text{O}_8 + 2 \text{Al}^{3+} + 7 \text{H}_2\text{O} = 3 \text{Al(OH)}_3 + \text{Na}^+ + 3 \text{SiO}_2 + 5 \text{H}^+,$$

much more aluminum must be added at the beginning of...
A. Accumulation and crystallization of allochthonous elements transported in solution
0: anhedral crystal of augite showing parallel cleavages and transverse fractures;
1: incipient weathering to iron oxyhydroxides along part of the cleavages, fractures and boundaries;
2: advanced stage of weathering, with enlarged open fractures, minute denticulate residues and many porous volumes;
3: final stage of weathering, and formation of a regular - irregular septo-alteromorph of goethite;
4: further evolution with infillings of gibbsite in all the open spaces: CUMULO-SEPTO-ALTEROMORPH.

Note: This type of infilling is easily distinguished from the ortho-polyphane alteromorph to goethite + gibbsite shown in Figure 8 C; open fractures can be seen within and between the neighboring minerals, and allochthonous gibbsite also may infill all the transmineral and intermineral fractures and all the neighboring "pores" alteromorphs.

B. Accumulation of allochthonous material transported as detrital particles
0: anhedral crystal of feldspar showing some subparallel intramineral fractures;
1: incipient weathering to gibbsite according to peripheral, linear and patchy patterns;
2: more advanced weathering: irregular septa of gibbsite and peripheral voids are formed around cavernous residues;
3: complete weathering to a glomer- septo-alteromorph of gibsite and incipient infilling by laminated material;
4: partial infilling by material, which leaves empty channels: CUMULO-GLIOMERO-SEPTO-ALTEROMORPH.

Note: For detrital particles to be deposited, part of the residual pores must necessarily be in free communication with transmineral or intermineral fractures around the alteromorph without forming closed volumes. Microlaminated deposits of detrital material can be expected at any stage of weathering, as soon as accessible residual pores are developed.

C. Accumulation of allochthonous material gradually as weathering progresses
0: anhedral crystal of quartz exhibiting irregular intramineral fractures;
1: incipient dissolution of the quartz and development of internal and peripheral pores along fractures and boundaries;
2: first crystals of gibbsite of allochthonous origin develop along open fractures and peripheral pores;
3: widened residual pores and residual cavernous cores surrounded by growing crystallaria of allochthonous gibsite;
4: glomer- and botryomorph patterns of the gibbsite accumulations: CUMULO-KOLO-ALTEROMORPH.

Note: If no residual quartz is observed within the partial cumulo-alteromorph, it will not be possible to ascertain the origin of the alteromorph, which can result from the infilling of the cavity left by dissolution of any mineral (e.g., quartz, calcite, apatite). The weathering of an aluminum-rich primary mineral can give rise to a similarly textured glomer- or botryo-alteromorph.

Figure 40. Evolution of cumulo-alteromorphs.
the formation of the gibbsite septa, and consequently much more aluminum must be imported from the neighboring grains of feldspar. This results in the formation of a residual pore-volume much greater than in the case of the weathering of anorthite. In both cases, the number and thickness of the septa are similar, but the proportion of residual pores is very different. The glomeromorphic part of the alteromorphs formed after anorthite is important (glomer-o-septo-alteromorphs), whereas the areas between the septa in the alteromorphs after albite are practically empty (true septo-alteromorphs).

Each grain of feldspar successively plays the same role. In the incipient stage of weathering, when the septomorphic texture is formed, the feldspar crystal receives aluminum from the superjacent grains of weathering feldspar. Thereafter, when the stage of formation of the glomeromorphic texture is reached, the feldspar grain loses a part of its original aluminum, which promotes (a) the formation of gibbsite in the subjacent grains of weathering feldspar, and (b) the formation of porous volumes in the grain being considered.

Similar processes probably are active during the ferrallitic weathering of ferromagnesian minerals to septo-alteromorphs of goethite. The crystallization of these distinct secondary minerals (gibbsite and goethite) from neighboring grains of feldspar and pyroxene promote the transfer of aluminum and iron only to the alteromorphs after feldspar and pyroxene, respectively. No aluminum is added to, and no gibbsite is observed in, the septo-alteromorphs after pyroxene, whereas no iron is added to, and no goethite is observed in, the alteromorphs after feldspar. Each septo-alteromorph only contains the dominant insoluble element that is specific to the primary mineral from which it developed.

Nevertheless, once the alteromorphs after feldspar, for example, are completely developed, equilibration between their chemical balances can reasonably be assumed by the fact that each alteromorph has gained, on average, early in its development, an amount of aluminum equal to that it will lose during the final step of its weathering. All feldspar crystals have reacted in the same way. In this case of isovolumetric weathering, the mass of the gibbsite crystals in a given alteromorph probably corresponds to all the aluminum originally contained in the parent feldspar grain. In observations of thin sections, it is noteworthy that the weathering of the alkali feldspar of granitic rocks produces very porous septo-alteromorphs, whereas the calcium-rich feldspar of basic rocks gives rise to less porous alteromorphs. This conclusion can also be reached by simply considering the chemical formula of the original feldspars. Anorthite contains twice the amount of aluminum as does albite. Nevertheless, a comparison of the chemical reactions shows why both feldspars, although they have very different aluminum contents, exhibit similar septa, and why they differ only in the glomeromorphic part of their alteromorphs.

The origin of the infillings may also involve transfer over much greater distances. The solutions may be extracted from the upper parts of the profile, or from parts of the landscape further upstream. Crystallization occurs in the porous alteromorphs if they are located in sites of absolute accumulation. Under such conditions, not only the alteromorphs, but also all types of open space (e.g., vugs, open fractures, dissolution-induced voids) can be filled by allochthonous transfer over long distances. The similarity of the products of infilling in both alteromorphic and extra-alteromorphic host textures allows one easily to distinguish the allochthonous part from the authigenous part of the secondary products, where present together within cumulo-alteromorphs.

In tropical countries, allochthonous gibbsite and iron oxyhydroxides are most common as infillings of porous alteromorphs. Under topographically, environmentally or climatically specific conditions, crystallization of calcite, quartz, chalcedony or gypsum also can develop. These deposits occur as holocrystalline microcristallites (crystallaria*) where they fill three-dimensional pores, or as crystalline banded structures (coatings*) where they fill open linear features or planar fractures.

The accumulated minerals are genetically independent of the secondary products that constitute the host structure, although under certain circumstances, both materials may consist of the same mineral species. For example, in septo-alteromorphs of gibbsite after feldspar, residual voids may later be filled by a second generation of gibbsite of allochthonous origin.

Authigenic and allogetic materials occurring in a given cumulo-alteromorph generally exhibit rather different microstructures. Allogenic deposits of transported particles form complete or crescent-shaped coatings, whose individual units are parallel to the walls of the former voids. Discordance in optical orientations results between authigenic and allogetic materials. Allogenic crystals formed from solution grow outward perpendicular to the walls of the voids. Concordance in optical orientations between the two generations of crystals is widely observed. In the latter
case, where both generations of crystals consist of the same mineral species, it may be difficult to identify the cumulomorphie character of the alteromorph.

More contrasted cumulo-alteromorphs are observed, for example, where koilo-alteromorphs after quartz are later filled by gibbsite in a bauxitic horizon, where septo-alteromorphs of gibbsite after feldspar are filled by clay coatings in a ferralitic soil, and where glomero-alteromorphs of gibbsite after feldspar are filled by iron oxyhydroxides in a ferruginous duricrust.

Some alteromorphs also may have their mineralogical content modified or replaced by transported elements. The ionic constituents of the solution react with the autochthonous minerals of the alteroplasma and transform them into a second generation of secondary minerals. In this way, septo-alteromorphs of gibbsite after feldspar may be transformed into septo-alteromorphs of kaolinite by vertical or lateral transfer of silica. The neoformed kaolinite progressively replaces the gibbsite crystals, and an ephemeral transitory composite alteromorph is developed. The regular shape of the original septa is disturbed or obscured, their volumes decrease, and they are fragmented as minute remnants in the increasing volumes of kaolinite. Ultimately, the kaolinite totally replaces the gibbsite; a new meta-septo-alteromorph (from the Greek μετα = after) is developed, in which traces of the first-formed septa are in some cases preserved as irregular lineaments of iron oxyhydroxides deposited in the median plane of the early-formed gibbsite-bearing septa.

The infillings can also be of detrital origin (Fig. 40B) and correspond to deposits of particles transported by circulating waters in the networks of open fissures. These deposits occur as coatings* and have a varied mineralogical composition. They are mainly clayey coatings (agillans*) or coatings composed of a mixture of clays and iron oxyhydroxides (ferri-agillans*). Deposits of detrital crystals of gibbsite also occur. Microcrystals of detrital gibbsite are oriented with their Z axis parallel to the walls of the pore, whereas gibbsite microcrystals deposited from solution should be oriented perpendicular to these walls. The agillaceous deposits are commonly finely microstratified or microlaminated, and consist of alternating deposits of material of distinct grain-size (clays and silts) or of distinct mineralogical composition (kaolinite and oxyhydroxides of iron).

Cases of transformation of kaolinitic ferriargillans into gibbsite and iron oxyhydroxide microcrystals can be found in old lateritic bauxite and ferruginous duricrust (Boulange et al. 1975). The ferriargillans are first deposited as allochthonous particles in the pores of the host material. This material may consist either of an alterite resulting from relative accumulation, or of an aluminous or ferruginous duricrust. When the leaching conditions become more extreme, the ferriargillans are rendered unstable, and they transform into gibbsite and iron oxide by desilication. The kaolinite and iron oxyhydroxides that were intimately associated within the previously formed coatings are now converted to distinct microstratified cutans of gibbsite (gibbsans*) and hematite (hematans*); several successive distinct layers of banded textures can be formed in replacement of a single clay cutan. These neoformed complex cutans resulting from absolute accumulation are superimposed upon pre-existing volumes of gibbsite and hematite resulting from relative accumulation, developed from the weathering of primary minerals. The secondary concentrations of allochthonous gibbsite may in some instances represent an appreciable amount of the total aluminum content of the bauxite (Bocquier et al. 1983). These secondary products of a second generation, where developed within previously formed poro-alteromorphs, give rise to meta-cumulo-alteromorphs.

Koilo-, septo- and glomero-alteromorphs (Fig. 40C) are the most suitable host structures, owing to an important volume of residual voids (commonly interconnected with the general pore-space of the alterite), although botryo-, phyllo- and other porous alteromorphs may also occasionally be filled. Even tho holo-alteromorphs, which exhibit a porosity too fine to be easily observed by optical microscopy, can be the sites for allogenic accumulations by diffusion and precipitation of mobilized elements circulating in the adjacent pores.

For example, holo-alteromorphs of "iddingsite" after olivine can be partly darkened by influx of manganese oxyhydroxides along transmineral fractures, and holo-alteromorphs of a smectite after pyroxene can become irregularly colored by addition of an iron pigment.

Polygenetic (alteration and weathering) processes and polyphase (alteration or weathering) products can give rise to "poro"-alteromorphs that are influenced by later processes of accumulation. In this manner, very complex alteromorphs may develop under the combined effects of all these processes.

Certain kinds of "poro"-alteromorphs are easily infilled by allochthonous material. These are the alteromorphs whose open pores are directly connected with the intermineral or transmineral pores. Retiporo-alteromorphs (Fig. 41) provide a good example.
A common example includes the weathering of nepheline to gibbsite after an intermediate stage of an isotropic (amorphous) material that readily becomes divided according to a hierarchical and reticulate network of shrinkage-induced cracks. Nepheline is observed mainly in relatively aluminum-rich alkaline rocks. During weathering, large quantities of aluminum are mobilized in the upper saprolite, and can ultimately crystallize as gibbsite crystals, of allochthonous origin, in all the pore space developed in weathered rocks lower in the profile, in particular within retiporo-alteromorphs after nepheline. Once most of the nepheline is replaced by a retiporo-alteromorph (Fig. 41A) of isotropic material, accumulations of gibbsite may occur within the reticulate network of cracks (Fig. 41B) before the isotropic material has itself been replaced by autochthonous gibbsite (Fig. 41C).

In these alkaline rocks, an early hydrothermal process has commonly converted a portion of the nepheline crystals to an assemblage containing mesocrystalline natrolite (Fig. 42A). If relics of nepheline are spared by this process, they will later be weathered successively to a retiporo-alteromorph of isotropic material, which is subsequently converted to gibbsite. The natrolite part of the alteromorph is directly weathered to compact assemblages of gibbsite crystals without passing through the isotropic material. Since the replacement of the natrolite generally starts long before the replacement of the isotropic material, both secondary phases can coexist (gibbsite after natrolite and isotropic material after nepheline).

If an allochthonous accumulation of aluminum occurs at this stage of evolution, the gibbsite will crystallize within the reticulate network of open cracks of the retiporo-alteromorph without modifying the isotropic material. Two different cases can arise after the appearance of this first complex alteromorph.

Firstly (Fig. 42B), the residual volumes of isotropic material are dissolved without formation of further secondary minerals. The compact gibbsite formed at the expense of natrolite coexists with the gibbsite of allochthonous origin, whose crystals are aligned in a reticulate assemblage of septa. This last assemblage reproduces, in a negative manner, the reticulate network of cracks. Large polygonal pores are observed in the part of the alteromorph formed at the expense of nepheline, whereas no interstitial pores are apparent in the part formed at the expense of natrolite.

Secondly (Fig. 42C), the residual volumes of isotropic material formed after nepheline are replaced, either by individual small centiporo-alteromorphs (in the largest volumes), or by minute holo-alteromorphs (in smaller volumes). In this last case, the distinction between the three successive generations of gibbsite is not always obvious in thin section. The complex alteromorph formed after nepheline exhibits compact assemblages of three successive generations of gibbsite. Autochthonous gibbsite (G1), formed at the expense of natrolite, is associated with compact reticulate septa of allochthonous gibbsite (G2), formed at the expense of the reticulate network that encloses compact or essentially nonporous assemblages of autochthonous gibbsite (G3), formed at the expense of the isotropic material developed from the residues of original nepheline.
FIGURE 41. EVOLUTION OF COMPLEX CUMULO-RETIPORO-ALTEROMORPH.

A. Normal weathering of a mineral without absolute accumulation of allochthonous material
0: euhedral crystal of nepheline;
1: incipient weathering of the crystal to isotropic material according to an irregular pellucidual and speckled pattern;
2: the nepheline crystal is reduced to an irregular cavernous central core surrounded by the isotropic material;
3: the few residues of nepheline are embedded in isotropic material microdivided as a result of a shrinkage process;
4: a hierarchized network of open fractures develops in the isotropic material: RETIPORO-ALTEROMORPH.

Note: This example of weathering without accumulation of allochthonous material is provided to better visualize what can happen if the alteromorph evolves further. Note that the first-formed straight fissures are widened when further fissures develop; in this way, a regularly hierarchized network of open fissures progressively develops in the isotropic material.

B. Absolute accumulation of gibbsite within a retiporo-alteromorph
0: euhedral crystal of nepheline;
1: nepheline crystal is reduced to a cavernous central core surrounded by slightly fissured isotropic mineral;
2: few residues of the primary mineral remain in the isotropic material, whose reticulate network of fissures develops progressively;
3: retiporo-alteromorph in which polyhedral volumes of isotropic material are isolated by open hierarchical fissures;
4: later accumulation of gibbsite within the reticulate network of fissures: CUMULO-RETIPORO-ALTEROMORPH.

Note: This second example normally replaces the previous one when the rock undergoing weathering is located in a zone of absolute accumulation, either in the profile or in the landscape. This example shows that the development of gibbsite in the network of fissures can occur before the isotropic material has evolved to crystalline secondary products.

C. Absolute accumulation of gibbsite within a more evolved retiporo-alteromorph
0: euhedral crystal of nepheline;
1: few residues of nepheline within an isotropic material, covered by a reticulate network of fissures;
2: retiporo-alteromorph consisting of polyhedral volumes of isotropic material isolated by open hierarchical fissures;
3: absolute accumulation of gibbsite in the network of fissures, whereas the isotropic material is not yet modified;
4: isotropic material replaced by autochthonous gibbsite: CUMULO-RETI + ALVEOPORO-ALTEROMORPH.

Note: Differences between absolute and relative accumulations of gibbsite are not easily distinguished if the successive stages of evolution are not concentrically disposed, with a central part of retiporous isotropic material only, an intermediate zone of absolute accumulation of gibbsite around the isotropic domains, and an external part with combined accumulations.
PART 3: ALTEROMORPHS

FIGURE 41. EVOLUTION OF COMPLEX POLYGENETIC AND POLYPHASE CUMULO-ALTEROMORPHS.

A. Partial alteration of nepheline in natrolite, and later weathering to isotropic material
0: euhedral crystal of nepheline;
1: nepheline is partly altered (first stage) to natrolite according to discontinuous pellicular and linear patterns;
2: residual nepheline is partly weathered (second stage) to isotropic secondary material showing incipient fissuring;
3: development of the reticulate texture in the secondary material, whereas natrolite is not yet weathered;
4: natrolite is weathered to a compact assemblage of gibbsite crystals: POLYPHASE - POLYGENETIC ALTEROMORPH.
Note: The weathering of the natrolite to gibbsite generally starts, develops, and is achieved before the later evolution of the isotropic material formed at the expense of the nepheline residues. Both secondary phases can coexist for a long time if absolute accumulation of aluminum does not occur. The polygenetic aspect is due to the occurrence of two distinct stages.

B. Infilling of the reticulate pores by gibbsite, and dissolution of the isotropic material
0: euhedral crystal of nepheline partly altered to natrolite;
1: alteration of the nepheline to isotropic material, which leaves coarse residual cores of the primary mineral;
2: weathering of natrolite to authochthonous gibbsite, and of nepheline to reticulate isotropic material (Fig. 42 A4);
3: infilling of the open reticulate fissures by allochthonous gibbsite, whereas isotropic material still persists;
4: dissolution of the isotropic material: the compact gibbsite after natrolite coexists with the reticulate gibbsite.
Note: Both generations of gibbsite are generally clearly distinguished in thin section by the assemblages in the crystalline units: compact assemblage of gibbsite after natrolite and reticulate porous assemblage of gibbsite after nepheline (POLYGENETIC ALTEROMORPH); this case seems to be the most common in weathered alkaline rocks.

C. Infilling of the reticulate pores and later evolution of the isotropic material to gibbsite
0: euhedral crystal of nepheline partly altered to natrolite;
1: weathering of the nepheline to isotropic material, with large residual cores of the primary mineral;
2: weathering of natrolite to pore-free gibbsite, and of nepheline to the reticulate isotropic material (Fig. 42 A4);
3: infilling of the reticulate fissures by allochthonous gibbsite before weathering of the isotropic material (Fig. 42 B3);
4: gibbsite crystallizes at the expense of the isotropic material: HOLO + CUMULO-RET + ALVEOPORO-ALTEROMORPH.
Note: The three generations of gibbsite are not always clearly distinguished in thin section: the irregular and randomly distributed pores, appearing only in the porous (alveoporo-) part of the alteromorph after nepheline, are generally too small to be clearly distinguished from the compact (holo-) part, after natrolite (POLYGENETIC ALTEROMORPH).
Some alveoporo-alteromorphs can develop by late partial and irregular alteration or degradation of the unstable secondary products, which were first developed in a nonporous or only slightly porous alteromorph. They are not true alveoporo-alteromorphs (ortho-alveoporo-alteromorphs), but rather polygenetic structures (para-alveoporo-alteromorphs) whose origin is in some cases recognized only with difficulty. Here, the accumulated material has an autochthonous origin; it is genetically associated with the first-formed secondary product, and it consists of elements showing relative accumulation within a pre-existing alteromorph (Fig. 43).

For example, an orthopyroxene crystal can be completely weathered, in the lower part of a profile, to a compact holoalteromorph of a smectite-group mineral. During a further stage of weathering, in the upper part of the profile, the secondary smectite becomes unstable under the new geochemical conditions, and is degraded in irregular patches, which are efficiently replaced by residual irregular alveolar pores. All these pores are internally rimmed with iron oxyhydroxides, which contrast, by their dark brown color, with the paler yellow-green color of the surrounding smectite. The iron oxyhydroxides host the immobile elements of the previously formed smectite; the deposit consists of autochthonous material of relative accumulation.

In this case, a para-alveoporo-alteromorph is developed. It must be emphasized that the distinction between ortho- and para-alveoporo-alteromorphs is not always as easy as in the above example. The late weathering of the first-formed alteroplasma does not necessarily promote the development of a different second plasma. It can only promote the development, by dissolution, of empty alveolar pores whose morphology may be identical to the morphology of the pores that form directly, at the expense of residues of the primary mineral, during the development of the first-formed alteroplasma. Deposits of iron oxyhydroxide not only appear as an internal rim around alveolar pores, but also as an overall rim developed around the alteromorph by peripheral degradation of its content of smectite-group minerals. A wide iron-rich rim delineates a peripheral envelope, which consequently encloses several small rims randomly distributed within the partly degraded green-colored smectite.

It is obvious that all these subtle distinctions among various alveoporo-alteromorphs are useful only where chronological evolution of the weathering profile and minerals is to be established. Otherwise, they can be disregarded.

- An ortho-alveoporo-alteromorph (from the Greek ὀρθός = straight, upright, direct) is a monogenetic alteromorph whose alveolar pores develop at the same time as the alteroplasma that contains them. The proportion of alveolar pores is related to the extent of leaching of the elements not incorporated in the alteroplasma.
- A para-alveoporo-alteromorph (from the Greek παρά = near, beside) is a polygenetic alteromorph whose alveolar pores develop (or increase) by irregular degradation of the alteroplasma itself and by the leaching of a part of its constituents. A second generation of distinct alteroplasma may well be genetically associated with this newly formed pore-space.

The development of monogenetic but two-phase alveoporo-alteromorphs may occur in the case of uninterrupted but slow weathering of coarse-grained weatherable primary minerals. These crystals are partly weathered in the lower parts of the profile. However, because they are coarse, their weathering is not complete once they are brought into the upper parts of the profile, by superficial erosion and relative subsidence of the weathering front. There, they are subjected to conditions of more extreme weathering. The residues of primary mineral are then weathered to a distinct alteroplasma of different mineralogical composition and textural appearance. The alveoporo-alteromorph that results after the complete disappearance of the last primary residues is very similar to the alteromorph of
Figure 43. Illustrations of alteromorphs to illustrate their further evolution. Distinction between an ortho-alveoporo-alteromorph and a para-alveoporo-alteromorph.
the previous example. Although both alteromorphs are structurally very similar, their development is genetically very different.

For example, a macrocrystal of pyroxene is first partly weathered along its transmineral fractures to smectite-bearing banded alteroplasmas that surround several residues of unweathered material. This first stage of partial weathering develops in the lower part of the profile; the normal evolution of such a partial alteromorph promotes, for example, the development of a purely smectite-bearing holo-alteromorph if the weathering conditions are not modified. Later (higher in the profile), when the conditions of weathering are modified, the pyroxene residues are weathered directly to iron oxyhydroxides organized around empty alveolar pores without passing through the stage of smectite development. The weathering process is more drastic, and the volume of exported elements is greatly increased. All primary residues are replaced by irregular alveolar pores, which are all coated by a rim of iron oxyhydroxides. This rim, along its external side, is molded against the smectite-bearing alteroplasma previously formed in the lower part of the profile, and which is not affected because it is more stable than the pyroxene residues. The completely developed alveoporoid-alteromorph then consists of a subcontinuous web of a smectite-group mineral that surrounds several alveolar pores, all coated by an internal rim of iron hydroxide.

The detailed study of such polyphase alveoporoid-alteromorphs allows the identification of their complex history and their distinction from other alveoporoid-alteromorphs. Crystallites of goethite that developed directly at the expense of the pyroxene residues have partly maintained the optical orientation of the original crystal of pyroxene, whereas crystallites of goethite formed at the expense of the smectite do not exhibit such a specific orientation.

The presentation of more detailed examples of complex weathering is not deemed necessary, but it is obvious that many other specific cases can be encountered in weathered profiles. No micromorphologist can claim to have observed, described and classified all the possible complex patterns of alteration and weathering.

The classification of compound alteromorphs is made according to the following genetic criteria, on the basis of identification of the mineralogical compositions and recognition of the textural patterns in which these minerals are associated.

- A monogenetic polyphase alteromorph results from the alteration or weathering, during only one stage of hypogene or supergene origin, of a primary mineral to an association of two or more distinct secondary minerals. One of these secondary minerals may be ephemeral and transitory to the second one, or the relative abundance of the two minerals may be dependent on the equilibrium conditions at the time of formation.

- A polygenetic polyphase alteromorph results from the alteration, in two or more successive stages (independent and well separated in time), of hypogene or supergene origin (or both), of a primary mineral to an association of two or more distinct, generally stable secondary minerals, successively formed under gradually modified conditions.
A whose Z axis lies in the plane of the thin section, has been weathered to a very porous septo-alteromorph of oxyhydroxides of iron. The transverse fractures that have localized the first stage of weathering are clearly visible across the alteromorph. The weathering front, under conditions of efficient leaching, has progressively encroached upon the pyroxene cores by following the regular and very fine cleavages of the primary mineral, which results in the formation of very thin and regularly parallel septa enclosing many elongate empty residual pores. The first photomicrograph, in PPL, shows the appearance of the alteromorph after the final phase of its development. During a later step of absolute accumulation of aluminum, the empty pores were infilled by secondary crystals of gibbsite, which appear clearly only in the second photomicrograph, taken in XPL. The late crystallization of the gibbsite seems to have left undisturbed the thin and delicate texture of the previously formed septo-alteromorph. The high aluminum content of the final alteromorph can only be attributed to an accumulation of allochthonous origin, because the original orthopyroxene contains practically no aluminum.
This photomicrograph shows an example of a cumulo-septo-alteromorph, whose formation and further development are rather similar to those in the two previous illustrations. The rock is completely weathered, and no remnants of the primary mineral are visible in the entire thin section. For this reason, it is impossible to define the exact origin of this alteromorph, which is definitely attributable to the weathering of a ferromagnesian mineral.

The section of the mineral is uneven; both cleavages and irregular fractures are responsible for the irregularly crossing septa. No specific texture is visible that can provide further insight. The observed alteromorph is an irregular (complex) septo-alteromorph. During a later step of absolute accumulation, crystallaria of gibbsite are formed in each cell delimited by the septa. This step results in the development of a cumulo-septo-alteromorph whose main characteristics are similar to those of the previous photomicrographs. An illustration taken in PPL does not accompany this XPL photograph because it would show only the network of dark brown septa, without any further information.
A strongly weathered clinopyroxene has been altered to a two-phase alteromorph consisting of magnetite and well-oriented talc. The rim of secondary magnetite continuously surrounds the alteromorph, as is usually the case in such alteration, whereas primary magnetite is still visible along the traces of the original protoclastic fractures. The rock is extensively weathered: the clinopyroxene crystals, which surround the talc alteromorph after olivine, are strongly weathered to a yellowish saponitic secondary product, which encloses many small denticulate remnants of primary pyroxene (D–E1, E2, E3). The proximity of an important network of fissures of supergene origin has promoted the partial alveolization of the talc area. The large pore was not generated during the alteration of the olivine into talc, which led to the formation of a holo-alteromorph, but much later, under the influence of a pedogenetic process. The alveolized original holo-alteromorph has become a para-alveoporo-alteromorph. The central pore, connected with the general pore-space of the weathered rock, has been largely infilled by deposits of reddish brown clayey coatings. This absolute accumulation of particulate material within the alteromorph results in the formation of a cumulo-para-alveoporo-alteromorph. Note that the sheets of talc have acquired a yellow coloration owing to centripetal transfer of an oxide of iron.
THE NODULE of grains of the micaceous mineral, locally abundant, into large meso-altermorphs of vermiculite has produced an important increase in the original volume of the rock. This increase is expressed by the extensive fracturing of the grains included in the micaceous mineral, mainly those minerals that exhibit an elongate habit, like the prisms of clinopyroxene, and those that exhibit a perpendicular orientation, or nearly so, relative to the cleavage of the enclosing micaceous mineral. Fractures are perpendicular, or nearly so, to the long axis of the pyroxene prisms and parallel to the layers of the surrounding vermiculite. These large inter- or intramineral voids, developed either between the extremities of the prisms and the surrounding mineral, or within the included mineral, remain empty as long as these voids, in the lower levels of the profile, remain sheltered from any infilling of allochthonous material. But in the case illustrated here, that of a fractured rock sampled in the upper part of the profile, the illuviation process enhances the capacity of even the smallest fissure to serve as a conduit, allowing the empty voids opened in the lower horizons to be filled. The photograph shows thin coatings of dark reddish brown material (B1, C4), whose complex composition, determined by X-ray diffraction or by other physical and chemical methods, shows an irregular association of a smectite with iron-oxide-stained kaolinite. These open cracks are easy pathways not only for the illuviated materials, but also for water that will promote the weathering of the fractured minerals.

Each fragment of clinopyroxene exhibits, in the areas around the open fractures, an incipient weathering to yellowish smectite and a delicate denticulation of its extremities (A1, D3). In areas that are subject to easy circulation of water and to cumulative processes, the autochthonous smectite formed at the expense of pyroxene is partially degraded or invaded by iron-rich solutions, which transform the initial yellow-colored smectite to a more reddish brown product. This photomicrograph should be compared with illustrations 061, 062 and 143, 144.
The phylloalteromorphs, in the rock has been replaced by meso-alteromorphs of vermiculite during a first step of hydrothermal alteration in the contact aureole associated with the emplacement of a surrounding younger granite. The development of these meso-alteromorphs, with a large increase in volume, has promoted the formation of many trans-mineral and intermineral fractures within or between the neighboring grains of pyroxene, and the opening of many interlayer pores in the vermiculite-dominant alteromorphs, which are as a result turned into phyllophoro-alteromorphs. In the upper part of the landscape, weathering causes a dissolution of important quantities of silica, not necessarily recombined to form secondary silicate minerals. Most of the silica released from thick ferralitic profiles is transferred into the lower parts of the landscape, where it can be fixed as infilling material within the early-formed open pores. These photographs show interlayer infillings of secondary quartz in a phyllophoro-alteromorph of vermiculite. The quartz crystals have a tendency to crystallize perpendicular to the walls of the pores, as can be observed in the lower photograph, taken in XPL. Some phyllo pores are not infilled, possibly because they were not yet open at the time of the infilling, or because they were not connected with the large pores along which the transfer of silica occurred.
Phlogopite-rich clinopyroxenite
Koua Bocca, Côte d'Ivoire
Depth: 2 m
Cumulo-phylloroporothermoph after phlogopite
Objective: X 6.3
PPL and XPL

The chronological events in the history of this phylloporoalteromorph resemble those in the case of the previous alteromorph. The difference lies in the fact that this thin section is cut almost parallel to the quartz deposit, and not perpendicular to it as in the former example. Such a fortuitous orientation allows the internal texture of the deposit to be better observed. Most quartz intercalations are circular or elliptical, and they exhibit a concentric distribution of domain size and a radial orientation of their component crystals. Some large unoriented crystals of indeterminate origin also are found. The flakes of mica that surround the quartz intercalations are rarely cut parallel to their layer structure because, along the contact with the quartz infillings, they are generally obliquely oriented or even completely distorted. These circular intercalations of quartz, where observed perpendicular to the layers of the host mica, exhibit a thin lenticular shape.
This weathered rock is a biotite-bearing granite in which most of biotite crystals are replaced by a meso-alteromorph of kaolinite. This replacement is accompanied by a substantial increase in volume. This volume increase of one component of the primary rock is responsible for the opening of many trans- and intermineral fractures. This network of fractures provides the pathway for the absolute accumulation of material derived from the upper soil and weathered horizons, either as deposits of detrital minerals or as crystallaria of minerals formed directly from percolating solutions. This photomicrograph illustrates the case of an unweathered but exfoliated grain of biotite whose opened lenticular phyllopores are infilled by neoformed kaolinite. Where the kaolinite is imported as detrital particles, it usually forms true coatings in which particles are oriented parallel to the walls of the pore. In the case shown here, the kaolinite particles are all oriented perpendicular to the biotite layers against which they have crystallized.

This general rule of the perpendicularity of the minerals formed by crystallization from a percolating solution is valid not only for kaolinite, but also for many secondary minerals, such as sheet silicates, gibbsite, goethite, quartz (411, 412), or even secondary apatite (see 424, 425).
A micaeous mineral, probably phlogopite, has been completely dissolved, perhaps after its replacement by an ephemeral intermediate secondary mineral. This dissolution without any residual material has promoted the formation of a koiloalteromorph (koilo-pseudomorph), whose external boundaries contrast strongly with the iron-rich matrix in which it is embedded. The koiloalteromorph has been later infilled, as the interstitial empty pores of the duricrust, by crystals of gibbsite whose large size contrasts strongly with the size of the commonly observed crystals of gibbsite. Note the cubic shape of the gibbsite crystals and their twinned domains.
The sample under study is completely weathered to a septo-alteromorph of gibbsite; the septa are regularly oriented parallel to the cleavage of the original grain, and some cross irregularly the parallel septa along nearly perpendicular transmineral fractures. Most septa exhibit a median plane emphasized by deposits of oxyhydroxides of iron, which are related to the pattern of the first-opened fractures and cleavage planes. During the later evolution of the septo-alteromorph, in the upper part of the isalterite, the septa have been partially destroyed, to give large vugs interconnected with smaller inter-septa voids. The large pore and most of the smaller ones have later been infilled by allochthonous deposits of amorphous Al–Si products associated with appreciable but variable quantities of hydrated oxides of iron. Most deposits are microlaminated owing to the variable content of the ferruginous compounds. The largest-sized vugs are not completely infilled, and residual empty pores are maintained whose smooth margins are coated with a last thin layer of microcrystalline gibbsite, formed by in situ crystallization in the most strongly iron-depleted parts of the deposits. Gradually, as the iron content of the deposit is removed by dissolution, microcrystalline gibbsite can develop. The resulting alteromorph is a typical cumulo-septo-alteromorph.
420, 421
GRANITIC ROCK
BR. 158, Brazil
Sampled by F. Soubies
Depth: 2 m
Cumulo-glomerosepto-alteromorph after plagioclase
Objective: x 4
PPL and XPL

The next two show the rarely observed case of the late replacement of gibbsite crystals of a glomerosepto-alteromorph after plagioclase by newly crystallized kaolinite, owing to the absolute accumulation of silica transferred in solution from the upper horizons. In PPL, the kaolinite neoformations appear as yellowish material because of concomitant influx of an iron-bearing solution, whereas the gibbsite substrate remains colorless. Some vughs of the first-formed alteromorph are still closed, poorly accessible to solutions, and not coated by the newly formed kaolinite, whereas other vughs, probably connected with the general pore-space of the weathered rock, are coated by kaolinite in layers of variable thickness. Note that the vughs, whose usual shape is angular in a gibbsite alteromorph after plagioclase, now has a smooth and curvilinear shape. In XPL, the crystallinity of the gibbsitic material is clearly observed, whereas the coatings of the much less birefringent kaolinite are not clearly distinguished from the empty parts of the alteromorph. A detailed study of the kaolinite coatings shows that the particles are oriented perpendicular to the gibbsite crystals on which they are fixed, and that the irregularity of the substrate promotes the sinuous and convex (mamilated*) habit of the deposits of neoformed kaolinite.
The photographs show the spectacular case of a glomeroseptalteromorph after plagioclase, in which most of the gibbsite has been dissolved, giving rise to many large interconnected vughs (meta-alveoporo-glomero-septo-alteromorph). The relics of the septa and of agglomerated volumes have been coated by kaolinite, which crystallized in situ (cumulo-meta-alveoporo-glomero-septo-alteromorph). The ferruginous coating along the fissures that constitute the median plane of the septa is still perfectly distinguishable (C-D3), even if the gibbsite content of the septum has nearly disappeared. The kaolinite is slightly colored in the shades of pale yellow owing to a slight permeation of an iron-bearing solution. The kaolinite does not correspond to a true coating of detrital material deposited on the skeletal septa, but rather to a neoformation of secondary kaolinite derived from the later silification of the gibbsite. The convex shape of the kaolinitized volumes does not correspond geometrically to that of a detrital deposit, but to in situ crystallization of material. Where the residual pores are more open, the overgrowth of kaolinite is thicker. As the volume of gibbsite progressively diminishes, the inherited iron content of the alteromorph, which was previously disseminated among the gibbsite crystals, is now concentrated into darker irregular patches.
The congruent dissolution of ferroan calcite of the primary rock has given rise to many contiguous koilo-alteromorphs. Their volume and shape are maintained more or less undisturbed, owing firstly to the formation of residual iron- and manganese-rich deposits in the rim of each alteromorph (see photographs 126, 127 and 285, 286, which are taken from the same profile, and which illustrate the first and the last steps of weathering of the primary mineral). Secondly, important in situ crystallization of secondary apatite has strengthened the fragile koilo-alteromorphs. These secondary crystals of apatite are needle-shaped, and grow as radiating bundles on the substrate offered by the iron-rich rims. The high content of secondary apatite in all these cumulo-alteromorphs is due to the high content of primary apatite in the unweathered rock. The primary apatite is progressively dissolved in the upper horizons, the phosphate-rich solutions percolate through the profile and, when they reach the level of absolute accumulation, these solutions give rise to crystallization of secondary apatite. The phosphate accumulation reaches such an extent that these levels of absolute accumulation are actively sought in mining operations.
A plagioclase, presumably feldspar, has been completely weathered to colorless and homogeneous isotropic material. With aging, this material has become microdivided by a network of open fissures, forming a typical retiporo-alteromorph. The associated amphibole and magnetite undergo weathering later, in the upper horizons. Sampled near the weathering front, the feldspar-group minerals are the first ones to be weathered, and their alteromorphs may be subjected to all kinds of illuviations of material coming from the upper levels. The photomicrographs show the infilling of some retipores and of some of their branchings by introduced yellowish smectitic material derived from the upper parts of the profile, mainly from the alteromorphs after hornblende. Hornblende is the only primary mineral to release solutions whose composition is compatible with the formation of a smectitic secondary clay. Note that the isotropic material after feldspar has not yet undergone further evolution to crystalline secondary products. Observations made of thin sections from weathered rocks sampled higher in the profile indicate that this retiporo-alteromorph of isotropic material will be progressively replaced by irregular metaalveoporo-(retiporo)-alteromorphs of gibbsite.
428, 429

**NEPHELINE SYENITE (LUJAVRITE)**
Poços de Caldas, MG, Brazil
Depth: 1.2 m

Incipient evolution of a retiporo-alteromorph after nepheline

Objective: x 4
PPL and XPL

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A part of nepheline is partly weathered to a colorless isotropic material whose internal reticulation is more and more densely developed as areas more and more distant from the core are considered. The weathering developed according to a classical peripheral and centripetal pattern. The residual core, clearly visible in XPL, is intensely fissured. Minute crystals of pale brown rinkite (mosandrite?) and of pale green aegirine, a sodic pyroxene, are randomly distributed in both nepheline core and secondary material. These inclusions are less weatherable than is the nepheline, and they will be weathered only much later. Incipient infillings of allochthonous gibbsite are observed in the marginal retipores of the secondary product and in the interstitial areas between the neighboring grains of aegirine (A5). These photographs illustrate the early evolution of the isotropic material; they can be compared with the next photographs, representing a more advanced stage of weathering.

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**PART 3: ALTEROMORPHS**

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**CUMULO-ALTEROMORPHS**
The upper photograph shows a more advanced stage of the infilling of the retipores and of the replacement of the isotropic material after nepheline by crystals of gibbsite, whereas a large residual core of primary nepheline is still maintained in the central part of the retiporo-alteromorph. The reticular texture of the deposits of allochthonous gibbsite is not easily distinguished from the smaller crystals of gibbsite of autochthonous origin, developed from the isotropic material itself. The inclusions of rinkite (mosandrite?) are not weathered.

The lower photograph gives a detailed view of a part of the retiporo-alteromorph in which the retipores are infilled by crystals of allochthonous gibbsite, whereas the internal polyhedral volumes of isotropic material are not yet disturbed (or less so) by their own evolution to autochthonous gibbsite. The reticular texture of the gibbsite deposits is strongly related to the open fissures of the retiporo-alteromorph. Note that some inclusions of prismatic aegirine (E3, E5) are partly weathered to iron-rich secondary products.
These photographs illustrate a complex case in which the residual core of nepheline (A1, B2) has been directly weathered to fine-grained gibbsite; during an early stage of weathering (comparable to that in the previous cases), the peripheral part of the primary mineral had been weathered into a reticuloporo-alteromorph of isotropic material. The reticulopores of the marginal part of the alteromorph are infilled by coarse crystals of gibbsite, whereas the reticulopores of its inner part are infilled by fine-grained crystals of gibbsite whose textural pattern is strongly related to the reticular network of open fissures. The fact that a nepheline crystal may be weathered either to isotropic material or directly to gibbsite makes the resulting alteromorph a polyphase alteromorph; the polyphase character is also enhanced by the fact that the isotropic material itself will later be replaced by autochthonous gibbsite. Note that in this more advanced stage of weathering, the inclusions of rinkite (mosandrite?) are slightly weathered, and surrounded by a thin pellicular rim of iron oxyhydroxide.
These general views of a weathered crystal of nepheline show all its consecutive mineralogical transformations to be "clearly" distinguished. Firstly, during a hydrothermal phase, part of the nepheline crystal was replaced by natrolite (as can be observed in thin sections of neighboring samples; see 086, 087). Irregular patches of the first-formed natrolite were later weathered to relatively coarse gibbsite (A1, A2), whereas the nepheline residues were weathered to a retiporo-alteromorph of isotropic material. The later steps in the evolution of the isotropic material are: (1) opening of a network of retipores, (2) infilling of the retipores by allochthonous gibbsite, whose reticular textural pattern is clearly distinguished, (3) replacement of the isotropic material by crystals of autochthonous gibbsite, whose very fine grain-size contrasts sharply with that of the reticular gibbsite. Three generations of gibbsite are thus associated but clearly distinguished in this alteration: autochthonous, relatively coarse gibbsite after natrolite, allochthonous medium-grained gibbsite infilling the retipores, and allochthonous microcrystalline gibbsite derived from the evolution of the isotropic material. Small inclusions of rinkite (mosandrite?) are completely weathered to residual empty pores thinly rimmed by brownish secondary products.
NEPHELINE SYENITE (LUJAVRITE)
Poços de Caldas,
Minas Gerais, Brazil
Depth: 1.4 m

Absolute accumulations of gibbsite in fractured primary minerals
Objective: x 4
XPL

This sample was collected in the contact area with the unweathered rock, containing as main rock-forming minerals orthoclase, nepheline and aegirine, with subsidiary eudialyte and arfvedsonite. The photomicrograph shows an area rich in unweathered but fractured orthoclase, with most grains intentionally placed at extinction in XPL for better contrast with allochthonous accumulations of gibbsite (C5). The orthoclase is partially surrounded by nepheline grains, whose complete weathering has developed typical glomero-septo-alteromorphs (A5). Careful examination of the orthoclase crystals shows that the feldspar is not weathered, and that all the observed alignments of gibbsite are deposits that infill previously formed open transmineral fractures. Some rectilinear fractures (A3–C5) are obviously oriented along opened cleavages of the host grain of feldspar. The origin of the gibbsite is to be found in the large amount of aluminum leached from the completely weathered upper levels of this nepheline syenite, an especially aluminum-rich rock. The downward migration of aluminum-bearing solutions is naturally stopped, and an aluminum-rich phase is deposited and accumulated against the unfractured and non-porous unweathered rock. According to the isovolume concept, this cortex of partially weathered rock shows an appreciable increase of aluminum compared with the quantity of aluminum that this rock should have contained under conditions of better drainage. This photograph should be compared with 047.
A process has replaced a crystal of olivine with an association of three secondary minerals: talc, tremolite, and magnetite. The photomicrograph in PPL shows that the talc, the pale beige-colored material (C–D2), is the main product, whereas tremolite, appearing as colorless needle-shaped crystals (B1, C1), is restricted to the marginal part of the alteromorph, which is in contact with clinopyroxene crystals. The magnetite grains are mainly distributed in the peripheral part of the alteromorph. They accommodate the iron content of the original olivine, which does not enter the structure of talc nor that of tremolite to a significant extent. This complex transformation results in a typical polyphase alteromorph. Normally, the talc is homogeneously distributed within the alteromorph, without formation of alveolar pores. The alteromorph is a holo-alteromorph, as can be seen by observing the entire thin section. During a later step of supergene weathering, part of the talc was weathered, with the formation of a large irregular pore now surrounded by a thin rim of oxyhydroxides of iron, which makes the border of the pore brown-colored; this colored rim strongly contrasts with the unweathered talc. The holo-alteromorph was thus converted to an alveoporo-alteromorph. Since this pore was not formed by the alteration of the olivine crystal, but rather by the weathering of the talc, the alteromorph has become a para-alveoporo-alteromorph. The introduction of allochthonous iron-bearing compounds via the supergene system of fissures colors the margins of the talc (and also of saponite after clinopyroxene grains, A1–2), and leads to the formation of a meta-para-alveoporo-alteromorph.
A large crystal of clinopyroxene has been partly weathered. The phylloporo-alteromorph is composed of well-oriented flakes of saponite, and several remnants of the primary mineral persist. The regular orientation of the secondary product is clearly seen in XPL. This first step of weathering, under conditions of restricted leaching, began by the formation of a first banded texture along several intraminalar fractures, whose traces are still recognizable. In a later stage of weathering, under conditions of increased leaching, the residual cores of pyroxene were directly and completely weathered to oxyhydroxides of iron surrounding irregular residual pores. The secondary iron compounds do not form individual crystals around the residual alevolar pores, but rather they seem to have permeated into the previously formed clay minerals, forming hypocoatings that take on an unusual deep brown color all around the residual pores. The resulting alteromorph is a meta-alveoporo-alteromorph. Note that the flakes of saponite are only stained by these oxyhydroxides of iron; they are not deeply weathered, as is made clear by the fact that they maintain their uniform orientation and extinction angle in continuity with the unstained parts of the alteromorph.
These two photographs show a rather similar example of a polygenetic alteromorph after clinopyroxene. This example corresponds to a basal section of the primary mineral, as can be deduced from the internal microtexture of the domains of secondary products. These domains show the typical double orientation according to the orthogonal cleavages of the primary mineral (C3). With conditions of increasing leaching, part of the secondary product has been stained by oxyhydroxides of iron which, on one hand, possibly originate from the late weathering of remnants of pyroxene. On the other hand, they may have been transported via the interconnected network of inter-mineral pores, the proportion of which strongly increased during the last step of weathering. As in the former photographs, the two-step weathering of this clinopyroxene results in the formation of a meta-alveoporo-alteromorph which, from a genetic point of view, can also be considered as a polygenetic alteromorph.
During an early stage of hypogene alteration, an olivine crystal has been completely replaced by a holo-alteromorph of talc. The talc particles are microcrystalline and randomly oriented, whereas the traces of the original protoclastic fractures, coated by particles of magnetite, are well preserved. When subjected to late processes of weathering, in the upper levels of the alterite, the talc component of the alteromorph is partially degraded and dissolved, which leaves irregular residual pores variably coated by iron-rich secondary products. The shape and the distribution of the residual pores obviously do not correspond to the shape and distribution of ortho-alveolar pores that could have formed by late dissolution of the residues of primary olivine. The slow degradation of the alteromorph, its gradual replacement by secondary residual pores, and the irregularly distributed fillings of allochthonous oxyhydroxides of iron make this alteromorph a typical para-alveoporo-alteromorph. By definition, its pores are derived from the later degradation of the secondary products, and not from the primary mineral itself. To better visualize the morphological differences between the two types of alteromorph, the two next photographs illustrate the case of a typical ortho-alveoporo-alteromorph after orthopyroxene.
A portion of orthopyroxene has first been partially weathered to a yellowish smectitic secondary product, whose distribution is related to the occurrence of several transmineral fractures and whose optical orientation is related to the Z axis of the primary mineral. Gradually, as the intensity of leaching and the conditions of weathering became modified, the denticulate residual cores are no longer weathered to a smectite, but directly to oxyhydroxides of iron, which results in the development of many residual pores regularly rimmed by thin brownish deposits. The iron-poor composition of the orthopyroxene is responsible for this high volume of pores compared to the lower volume of oxyhydroxides of iron. Both mineral phases, the smectite-group mineral and the iron-rich secondary products, together with the residual empty pores, are directly derived from the weathering of the primary mineral; the alteromorph is an ortho-alveoporo-alteromorph. Since two different mineral phases are successively formed from the same primary mineral, the alteromorph is a two-phase alteromorph. Note that the characteristic denticulation of the pyroxene residues was clearly maintained during the second step of weathering. Several transmineral fractures have been more recently widened, and coated with deposits of ferruginous clays of allochthonous origin.
Cumulo-alteromorphs

446

Granitic Rock
Siagozohoin, Lakota.
Côte d'Ivoire
Sampled by B. Boulange
Depth: 2.4 m
Meta-alteromorph after biotite - kaolinite
Objective: \( \times 16 \)
XPL

447

Granitic Rock
Cataguases, MG, Brazil
Sampled by L.M. Lopez
Depth: 5 m
Meta-alteromorph after biotite - kaolinite
Objective: \( \times 16 \)
XPL

The two photographs illustrate a relatively common case of meta-alteromorphs: a primary mineral is completely weathered to a first secondary product, which is later replaced by a second one, the successive minerals exhibiting a progressively simpler chemical composition by progressive loss of their less soluble constituents. In both cases, a crystal of biotite was first weathered to kaolinite, with complete leaching of the very mobile potassium. The replacement results in an important increase in volume in a direction perpendicular to the layers of the primary mineral; a meso-alteromorph results. Later, in the upper horizons of the bauxitic profile, in which the alteromorphs are subjected to conditions of efficient leaching, the kaolinite itself becomes unstable, loses its silica, and is converted to gibbsite. In both photographs, taken in XPL, the kaolinite-rich parts of the alteromorphs exhibit their first-order grey interference-colors, whereas the lenticular domains of gibbsite are first-order white. The irregular dark patches that appear in the upper photograph are residues of the conductive coating of carbon deposited on the thin section in preparation for electron-microprobe analyses.
Within the isalterites, processes of supragene weathering have produced variably shaped and textured alteromorphs from practically all weatherable minerals present in the parent rock. In many cases, the resulting alteromorphs maintain some characteristic features of the primary minerals from which they have developed. This finding allows the identification of their origin, especially if thin sections of less weathered rocks are also available. Some of these characteristics are microtextural, others are geochemical or mineralogical, and yet others are linked to the relative spatial distribution of the minerals or to specific associations of minerals. On a larger scale of observation, most of the alterites have inherited the macrostructural and macrotextural features of the parent rock, such as specific stratigraphic, petrographic or tectonic features.

Among the features that are directly inherited from the primary mineral are the shape of crystals (automorphic or xenomorphic habit), the geometrical shape of their outlines (e.g., linear, curved, denticulate, irregular), the size and distribution of grains (e.g., phenocryst, porphyroblast, inclusion), the traces of cleavage and of intraminal fractures, in some cases enhanced by deposits of mineral particles, the optical orientation of the secondary product controlled by that of the primary mineral, and the occurrence of inclusions (e.g., their nature, distribution, and weatherability).

The distribution and spatial relationship of the minerals as they existed in the parent rock are also preserved within the alterite: major or accessory, isolated or agglomerated minerals, patterns of polymineralic associations, distinctive associations (symplectic textures, myrmekite, coronas), casual but characteristic associations (spinel + magnetite, epidote + hornblende, chlorite + titanite), included minerals (zoisite within plagioclase, hornblende within pyroxene) or minerals in interstitial positions (serpentine between olivine crystals, talc between orthopyroxene grains). All these features are clearly recognizable in completely weathered rocks.

At a higher level, the characteristic features of the parent rock, such as its texture (e.g., porphyritic, granoblastic, ophitic, poikiloblastic, lepidoblastic) and its grain size typically also are preserved. However, the original grain size cannot be clearly identified where the parent rock was very fine-grained, where the alteromorphs are polymineralic, or where the rock gives rise to many areas of crypto-alteromorphs. It must be kept in mind that the grain size of the parent rock, and even its mineralogical composition, may have been irregular, and may have exhibited important variations over the thickness of a weathered profile.

The chemical and mineralogical compositions of the alteromorphs, at least in the case of isalterites, are largely dependent on the composition of the primary minerals from which they develop. The autochthonous secondary minerals that form in an environment of relative accumulation inherit part of the chemical composition of the parent minerals according to physicochemical conditions prevailing in the lower part of the profile. The geochemical affinity between primary and secondary minerals necessarily defines potentially significant incompatibilities: an olivine crystal, which does not contain aluminum, is never weathered to gibbsite, and a nepheline crystal, which normally does not contain iron, is never weathered to goethite. If such incompatibilities are nevertheless encountered, a case of absolute accumulation of allochthonous material must be suspected.

The original structures inherited from the primary minerals are generally well preserved in alteromorphs of the first generation. The later degradation of the secondary minerals and their replacement by secondary minerals of a second generation tend, in contrast, to completely destroy these inherited structures in the modified alteromorphs. Where the processes of degradation and replacement have destroyed the largest part of the original alteromorphs in a given level of a profile, the isalterite is converted to an alloalterite.

Logical inferences based on likely and unlikely geochemical affinities, the tracing of particular characteristics, and of persistent signatures within the altero-
morphs, and repeated comparison with the reference material (the parent rock) all lead to, in most cases, the identification of the origin of the alteromorphs, the study of their development in time and space, and even a prediction of the pattern of their further alteration.

The classification of alteromorphs, such as it has been described above, has been established with the aim of simplifying the descriptive work of the observer. Some new terms coined from Greek and Latin roots commonly used in Earth Sciences have been proposed. The use of this new terminology does not introduce unexpected difficulty, because the new terms are simple and generally self-explanatory. The classification is not exhaustive; more kinds of specific alteromorphs will be discovered in the future, and new terms will be required to describe them.

Depending upon the aim of the observer, and the need for condensed descriptions, in order to avoid repetitive, long descriptions, completely developed alteromorphs can be classified and succinctly described by using the following different criteria.

- **Geometrical criteria** are purely descriptive, and based on the extent of conservation of the shapes and volumes of the primary minerals being replaced. These criteria give rise to a simple classification into iso-, meso- and kata-alteromorphs, to which can be added some specific cases, such as pseudomorphs, echino-, phanto- and crypto-alteromorphs.

- **Microtextural criteria**, which concern the internal distribution of the secondary products within the alteromorphs, are based on the lack of residual pores or of the secondary solid phase. The “end members” are holo- and koilo-alteromorphs, respectively. Between these two extreme cases is the very widespread and diversified group of the “poro”-alteromorphs. The complementary distribution of the solid and porous residual volumes is used as the basis for a more accurate classification. On the one hand, alveoporo-, centroporo-, phylloporo- and retiporo-alteromorphs result where the pore volume is characteristically distributed and completely embedded within the solid phase. On the other hand, botryo-, glomero- and septo-alteromorphs result where the pore volume is important, and where the solid phase is characteristically textured. Complex poro-alteromorphs can be described by the combination of two or more prefixes or by the introduction of new additional roots, as in the case of acantho-septo-alteromorphs.

- **Genetic criteria**, which concern the internal distribution of distinct secondary minerals and the history of their development before, during and after the formation of alteromorphs, are mainly used to describe and classify composite alteromorphs. These are polygenetic and polyphase alteromorphs. Most common alteromorphs are monophase and monogenetic. Alteromorphs whose pore volumes are modified, after their development, by invading allogetic materials are cumulo-alteromorphs, whereas alteromorphs whose unstable alteroplasmas are modified by later degradation or weathering are meta-alteromorphs.

In the isalteritic part of the profile, all weatherable primary minerals have been replaced by complete alteromorphs whose internal textural patterns and mineralogical compositions are commonly characteristic and closely related to the composition and texture of the parent rock and to the geochemical conditions under which these minerals have been weathered. In the alloteric part of the profile, these alteromorphs may become transformed or replaced by other alteromorphs (or other textural entities) whose size, shape, internal texture and mineral contents are progressively destroyed as the physical and geochemical conditions become modified. Contrasted cases of modified alteromorphs are observed, particularly within the levels in which processes of accumulation prevail.

Fragments of the original rock, primary minerals and alteromorphs in soils, colluviums, duricrusts and other near-surface horizons may reach such upper levels as undisturbed units. Their fate will depend on their weatherability and on the physical (erosion, transport, sedimentation) and geochemical (dissolution, replacement, cementation, induration) conditions to which these litho- or altero-relics are subjected. These near-surface processes generally differ strongly from the processes prevailing during the earlier history of alteration and weathering of the material, at lower levels in the profile. These superimposed modifications and transformations will be described and illustrated in the next part of this book.
A weathered clinopyroxenite, whose main constituents are clinopyroxene and magnetite, has been progressively replaced by yellowish goethite (with several small patches of hematite). The neoformed minerals have almost completely obliterated the alteromorphic textures of the weathered grains of clinopyroxene. The porous alteromorphs have been replaced by a compact and uniform matrix of goethite containing only minor pore-space. In contrast, the grains of magnetite are maintained within the alterorelic. Their distribution corresponds to the original distribution in the parent rock. The replaced alterorelic has been later transported and incorporated into a red soil S-matrix. An empty circum-nodular pore completely surrounds the alterorelic. For additional explanation, see photomicrograph 491.
CHAPTER 13
Definitions

LITHORELICS

Lithorelics are residual fragments of unweathered rock, a few millimeters to a few centimeters across, identifiable petrographically by their mineralogical composition and their texture. Lithorelics are embedded in a more evolved ground mass, which can be an alterite, a soil, a colluvial or alluvial deposit, a ferruginous crust, etc. Lithorelics are, by definition, composed of several mineral grains, of identical or distinct species. Most lithorelics have been displaced, and thus do not occur in their original environment.

Where the mineral grains are isolated in the groundmass, separated from their original environment, they are no longer considered as lithorelics, but rather as skeleton units: they are "residual minerals" or "skeleton grains". If they have a density greater than 2.89 g/cm³ (density of heavy liquids, bromoform or tetrabromomethane, used for their separation), they are also called "heavy minerals" (pyroxene-, amphibole-, olivine-group minerals and many other generally dark-colored minerals); otherwise, they are considered "light minerals" (mainly colorless minerals, such as quartz and the feldspars).

The associations of residual heavy minerals observed in alterites and soils, may, as with the lithorelics, be diagnostic of the original rock type; the identification of their paragenesis may be useful in mineral prospecting and in cartography. They are also useful in determining the degree of autotrophanous or allochthonous character of a weathering profile for pedological purposes, and in estimating the content of mineral nutrients in near-surface horizons for agricultural purposes.

The very weatherable heavy minerals are rarely observed in superficial loose materials. However, where they are observed, they are particularly valuable for the identification of the parent rock. In contrast, the ubiquitous minerals, commonly very resistant to weathering, generally are less useful.

ALTERORELICS

Alterorelics are residual fragments of weathered rocks, or relict assemblages of weathered minerals, isolated in a more evolved matrix. They are recognizable by their original petrographic textures and by the composition of their alteromorphs. These can, in many cases, be associated with less weatherable primary minerals. The alterorelics correspond either to previously formed lithorelics whose content and eventually texture, have been modified by weathering processes, or to relics of alterites (or of alteroplasmas) now isolated within a matrix that results from the progressive replacement of the alterite by a newly formed plasma of pedological origin (pedoplasma). Note that grains of weathered minerals, now isolated within a more recently developed matrix, must be considered as relict alteromorphs and not as alterorelics.

In the first category, two main types of alterorelics must be distinguished: those that have been weathered before their displacement, deposition and incorporation, and those that have been displaced as lithorelics and weathered after their deposition. If unweathered, or not yet weathered, the remnants of primary minerals are disregarded; the alterorelics are composed of variously textured alteromorphs as they were defined and described in the previous chapters.
**Pedorelics**

Pedorelics are, according to the definition in the glossary, "either features formed by erosion, transport and deposition of nodules of an older soil material, or pedological features from it, or by preservation of some part of a previously existing soil horizon within a newly formed horizon" (Brewer 1976). Especially if they have been transported, these pedorelics commonly consist of more-or-less indurated solid material, such as papules*, concretions or fragments of crust.

In the terminology used in surficial geology and geomorphology, all these relics are very commonly classified as "gravels", owing to their grain size, their hardness and their obvious transport and deposition. These gravels are generally hard and resistant, multi-millimetric residual features that have been displaced and redeposited within a horizon that is not their original environment. Their mineralogical nature can vary; they include litho-, altero- and pedorelics, large-size quartz grains, miscellaneous concretions, fragments of bauxite and iron-crust, charcoal residues, etc. The concept of their displacement and deposition is implicitly included in the definition of gravels; they are detrital materials. In many lateritic near-surface mantles, all these detrital units can later be surrounded by regular cortices (see below), which give them a more rounded and smooth shape.

**Concretions**

Pedologists generally use the term concretion to describe the volumes formed by local concentrations of compounds that cement the pre-existing mineral grains. Most cementing materials have an iron-rich composition, but manganiferous, calcareous, siliceous and, less commonly, gibbsite-rich concretions also occur. They commonly are rounded, mammillate, palmate or botryoidal, with a sharp boundary and properties that contrast with their matrix.

The mineralogical composition and the internal textures of these concretions vary according to the geochemical properties of the horizon in which they formed, or of the horizon in which they were deposited after their displacement. They can be crystalline or cryptocrystalline features. They can be homogeneous features from the standpoint of both their internal texture and composition. They may be composed of an assemblage of newly formed particles of plasma that cement the pre-existing skeleton elements. They may show a central part (nucleus) devoid of any texture or cortification, surrounded by a banded, or microlaminated, continuous and concentric texture (cortex).

Oritic and anorthic concretions are usually distinguished. In the former, the base material of the concretion is identical to that of the surrounding matrix in which they are embedded. In the case of anorthic concretions, the base material of the concretion and that of the matrix differ. The frequency of occurrence of anorthic concretions is generally much higher than would normally be expected. Indeed, the concretion-forming process exhibits a real tendency to operate in areas or matrix that have a different composition, or within or around allochthonous features that have been introduced within this matrix (lithorelics and alterorelics, for example).

**Pisoliths**

The term pisolith (from the Latin pisum = pea and from the Greek λάθος = stone) designates a concentrically textured, generally spherically shaped nodule, some millimeters in diameter, composed of an untextured nucleus surrounded by a microlaminated cortex. Both nucleus and cortex commonly are indurated or, at least, are rather harder than the surrounding matrix in which they are embedded.

This term will be used to designate the spherical nodules that characterize a particular facies of bauxite, called pisolitic bauxite.
CHAPTER 14
Composition, Origin and Morphology

LITHORELICS

Composition

Lithorelics are, by definition, undisturbed assemblages of unaltered primary minerals. Nevertheless, for pedological purposes, this definition must be extended to include the fragments of relict rock whose mineral constituents have been, at least partially, replaced by secondary minerals as a result of hypogene alteration. They are, for example, relics composed of tremolite, actinolite, epidote, serpentine, chlorite and other minerals of hydrothermal or metamorphic origin. These minerals are much more resistant to processes of supergene weathering than the primary minerals. As a result, they typically persist for a long time in the weathered or soil horizons. These relics must be considered, from a pedogenetic standpoint, as lithorelics and not as alterorelics.

Point of origin

Lithorelics can be formed at different levels of the profile. At the outcrop level, they can form directly by removal of rock fragments from outcrops exposed at the soil surface. In this case, the lithorelics commonly do not exhibit traces of weathering. In tropical regions, however, the lithorelics of mafic or ultramafic origin generally exhibit evidence of near-surface ferruginous weathering, or impregnations that would not occur if they had a different point of origin, within the lower parts of the profile, for example. Where isolated from the outcrop, the lithorelics are scattered down the slopes and are progressively incorporated into the near-surface horizon of soil, in which they may represent a significant fraction of the coarse skeleton grains. This first kind of lithorelics commonly exhibits an irregular and angular outline.

At the weathering front, lithorelics also can form by the fragmentation and removal of unweathered or irregularly weathered rock. This occurs at the base of shallow profiles, in which the soil horizons are subjected to slow creep down the slopes under the influence of the gravity. The rock fragments that are isolated at this level are preferentially concentrated at the base of the pedological horizons, in which they can form a coarse-grained deposit very similar to a stone line*. The lithorelics are commonly associated with coarse fragments of quartz released by the dismantling of quartz veins that run across the parent rock. Alterorelics may be associated with lithorelics of similar origin, but they are soon destroyed by creep-related movement, and their mineral content is incorporated into the soil material; their identification then is no longer possible. Such lithorelics commonly exhibit a more rounded shape than the lithorelics of the first category.

Lithorelics can still be formed within the alterites themselves, mainly where the parent rock is heterogeneous. The most weatherable part of the rock forms alterites and soil materials, whereas its most resistant parts (e.g., veins, metamorphosed layers) remain unweathered and suspended within the alterites or even within the soil horizons. There, they are progressively reduced to small fragments, and quickly incorporated in the groundmass of the alterites and soils. In this case, the mineralogical composition and the textures of the lithorelics differ from those of the main rock from which the alterites and soils were developed.

Rock fragments that are temporarily maintained within isalteritic horizons of identical origin cannot be considered as true lithorelics because they will "soon" be weathered, in a normal manner, and rendered unrecognizable as separate entities once integrated into their surrounding isalteromorphic matrix. In contrast, where the weathered layers are perturbed and transformed into alteritic horizons, the unweathered relics can be considered as true lithorelics, since they are now observed within a modified matrix that is not their own original matrix. This third kind of alterorelic exhibits in some cases a katamorphous texture, with cracks, irregular outlines, protruding parts and embayments.
Morphology

The boundaries of the lithorelics generally follow intermineral contact planes and transmineral discontinuities and cracks. This explains their sinuous and angular habit, which can persist as long as these relics have not suffered appreciable displacement or weathering. The lithorelics, where they occur in a near-surface horizon with which they have not necessarily a direct affinity, are generally of allochthonous origin. Their outlines are then more or less abrupt or rounded, according to the processes of transport (colluvial or alluvial) to which the lithorelics were subjected, and according to the extent of their displacement.

The sharpness of their outlines depends also on the grain size of the original rock, on the hardness of its mineral constituents, and on their physical properties. Fine-grained rocks usually give, at a macroscale, more rounded lithorelics having a smoother outline than the coarse-grained ones. The general shape of the lithorelic also depends on the texture of the rock and on the orientation of its mineral grains. Lithorelics from mica schists and gneisses tend to be elliptical, whereas basalts, granites and other unoriented igneous rocks give uneven lithorelics, without any particular shapes. The smoothness of their outline depends on the size of the mineral grains in the parent rock.

Among the most common rocks, basic and ultrabasic rocks, owing to their intermediate grain-size and to their equant texture, and gneisses and amphibolites, owing to their layered and oriented textures, are the rocks that most easily give rise to lithorelics. Granite, in contrast, do not easily give rise to lithorelics for three main reasons: (i) the relatively coarse grain-size of most granites does not allow small polymineralic relics to be formed (boulders and pebbles are more usually encountered), (ii) the slow and progressive weathering of the feldspar-group minerals does not allow the formation of a sharp weathering front and of polymineralic relics with sharp margins, and (iii) the mineralogical composition of products of their weathering does not allow the eventually formed alterorelics to be maintained for a long time as distinct and identifiable units.

Alterorelics after Granitic Rocks

The identification in thin section of alterorelics after granitic rocks is not always easy because they are essentially composed of quartz grains cemented by loose and poorly resistant argilliplasmas (alteroplasmas), whose composition and textures may be confused with the composition and textures of the surrounding pedoplas-
result of weathering of the primary residues they contain. The primary minerals of such alterorelics can in this way produce two or more secondary minerals, and they give rise to polyphase alteromorphs.

Whatever the isalteritic or alloteritic level in which they are encountered, these particular types of lithorelics will not be considered further in the remainder of this chapter.

Where soils and weathered horizons are locally cleared away by erosion, outcrops of unweathered rock may become exposed at the surface. Under these new conditions, numerous lithorelics are released from the rocks by physical disaggregation, and are mixed together, within the upper-slope colluvium or within the lower-slope alluvium, with gravels, sands, alteroplasms and pedoplasms. New pedogenetic processes operate, and produce new soil horizons in the upper part of these colluvial or alluvial materials.

This process of lithorelic formation is certainly the most efficient and the most widespread. All lithorelics have been displaced, and the distinctness of their shapes largely depends on the distances travelled from their source to the final site of deposition. The recorded variations in the petrographic nature of the lithorelics are rather representative of the petrographic diversity in the watershed, but they do not correspond necessarily to the rock type observed at the base of the profile studied.

In petrographically heterogeneous profiles, the lowering of the weathering front can also avoid, well above the weathering front and up to the pedological horizons, at least on the short term, rock fragments or rock layers that are more resistant to the weathering processes. These are generally rocks of different mineralogical composition or of different grain-size, such as, for example, mineral veins, metamorphosed wallrocks, and microgranular beds. These more resistant rocks, if they survive to become incorporated into the near-surface horizons, are subjected to processes of physical disaggregation. Small volumes of rocks are progressively isolated from their matrix by the development of an irregular but interconnected network of fissures, often coated by illuvial cutans, which finally completely surround them.

Under the influence of (i) surficial movements along the slopes, (ii) biological processes (roots, soil macro- and microfauna), and (iii) processes of erosion, these fragments are released from their original matrix and are mixed with the sandy or clayey matrices of the upper horizons, from which they differ in their texture and in their mineralogical composition.

Lithorelics are common not only in thick lateritic covers developed under humid conditions, but also in regions characterized by a relatively dry climate, in which alterites and soils are rather thin, and where outcrops of unweathered rock are common.

Where they occur near the surface, lithorelics very commonly give evidence of either lateral or vertical transport, because their mineralogical composition may be distinct from that of the surrounding matrix. Also, there may be important variations in their original mineralogical composition.

Lateral transport is the result of a mechanical process under whose influence lithorelics of miscellaneous origins are laterally transported, mixed together, and deposited in the lower levels of the landscape. Such lithorelics generally exhibit rounded shapes and a smooth outline.

Vertical transport results from differential erosion, which concentrates the lithorelics, in relative terms, in some levels of the profile, by selective removal of the small particles from the alteroplasms or pedoplasms that were cementing them. In this last case, the mineralogical composition of the lithorelics is commonly much more homogeneous, and the variations recorded are strictly local, within the thickness of the profile, in the parent rocks and the mineral veins that cut them. The lithorelics generally correspond to a less weatherable petrographic facies that is, to some extent, different from the overall petrographic facies of the enclosing rock. Their shapes are uneven, with an irregular and angular outline.
LITHORELICS

Illustrate the formation of several lithorelics at the expense of a highly resistant rock. The original rock, composed of clinopyroxene grains, is now converted to a very compact assemblage of tremolite and actinolite under the influence of hydrothermal alteration. The chemically resistant rock can be preserved until it reaches the shallow levels of the alteration, where it is subject to fracturing. An irregular network of curved and interconnected fractures divides the rock into irregular but undisturbed fragments. Most fractures are open and coated by thin deposits of clay minerals, deeply colored by oxyhydroxides of iron. Thin intraminal cracks, which also are colored by compounds of iron, cross all fragments of rock; they promote further divisions of the lithorelic. When subjected to erosional or to colluvial processes, these rock fragments become separated from each other and, mixed within the pedological matrix, they form isolated lithorelics, which lose their original orientation. They are then subjected to the weathering processes prevailing within the upper horizons. In most cases, these are very different from the conditions of weathering within the lower horizons. Fractures and cracks do not necessarily follow the intermineral boundaries: mineral grains may be cut in two or more parts (B4), whereas groups of grains may be maintained together without cracks (D4).
taken from the same upper level of the profile, show two steps of formation of isolated altero-lithorelics formed from an ultrabasic rock, mainly composed of clinopyroxene, magnetite and minor amounts of hornblende and mica. Most pyroxene grains are partly weathered to a smectitic clay mineral. The rock is fractured by many curved and anastomosing cracks, which mainly follow the contact between grains. The first photograph shows a slightly disturbed rock whose cracks are mostly coated by dark red clayey deposits. The second one shows that the separated altero-lithorelics begin to move differentially relative to one another and to be mixed with the pedological S-matrix of the upper horizons. Biotite-vermiculite crystals are visible in both illustrations at C1. The relative proportions of the remnants of primary mineral and of the secondary minerals within the rock fragments are practically equivalent. For this reason, such relics are better described as altero-lithorelics.
A large crystal of microcline includes several small euhedral crystals of plagioclase and anhedral crystals of biotite. The microcline host is chemically unweathered, whereas the grains of plagioclase were largely replaced by very fine particles of "sericite" (appearing pale grey in PPL); the "sericite" formed during an early stage of hydrothermal alteration. The grains of biotite were partly converted to vermiculite meso-alteromorphs exhibiting intramineral deposits of iron oxyhydroxides along some of their phyllopores. These photomicrographs show the break-up of the rock along a closely spaced network of interconnected fractures, which gives rise to many small lithorelics. It is obvious that such an interconnected network, visible in the two dimensions of the thin section, is also interconnected in the third dimension, and that all fragments of the rock are actually separated from each other. Most of the fractures were initially accordant fractures; however, the slow internal movements of the fractured rock result in the relative displacements of the fragments and in the obliteration of their regular and accordant boundaries. Most fractures are open and regularly coated by very well-oriented coatings of clay. Each rock fragment is composed of only one or two mineral grains. This explains the difficulty, in the case of such granites, to form true and durable lithorelics which, by definition, are polymineralic assemblages of minerals.
Formation of Lithorelics of Granitic Rock
Koua Bocca, Côte d'Ivoire
Depth: 1.8 m
Objective: x 1.6
PPL and XPL

These photographs illustrate another kind of lithorelic of a calc-alkaline granite that was previously subjected to hydrothermal alteration. Part of the plagioclase has been transformed to epidote, which exhibits the characteristic high interference colors under XPL (B2, C3). The more resistant quartz and microcline have not undergone any transformation. The rock contains an appreciable amount of hornblende and biotite; both minerals exhibit good cleavages, which allow the easy development of fractures and the isolation of the less breakable components. In these photographs, an important part of the peripheral fracture follows an alignment of the easily cleavable grains of biotite, whereas the other parts are largely infilled by clay deposits eroded from upper alteromorphs developed at the expense of mica and amphibole. Quartz, microcline and epidote, three very resistant minerals, form most of a polymineralic lithorelic, which may persist unweathered for a long time in the upper horizons of the soil profile.
LITHORELICS

Mafic rocks have been weathered into a smectitic secondary material near the base of the weathered profile, at more than 10 meters depth. Only a few islands of partly weathered material are still recognizable in the upper part of the profile because, in slightly metamorphosed parts of the rock, large prismatic crystals of clinopyroxene commonly are surrounded by plagioclase grains, which have undergone replacement by a highly resistant epidote-group mineral. The epidote appears, under PPL, as grey-colored areas, exhibiting a fine sieve texture; it partially surrounds the prismatic crystals and protects them from further weathering. Within the upper horizons, the conditions of weathering differ from those prevailing in the lower parts of the profile; the clinopyroxene crystals, although still protected, begin to weather into iron oxyhydroxides. Many denticulate remnants of clinopyroxene are identifiable within the dark brown material. The alterorelic is distinguished from the normal alteromorphs of the weathered rock only by the fact that the secondary products are not similar in the lower and in the upper parts of the profile.
Lithorelic temporarily preserved within isalteritic material

**CLINOPYROXENITE**

Koua Bocca, Côte d'Ivoire

Depth: 1.2 m

Objective: × 4

PPL and XPL

These microphotographs illustrate in greater detail the weathering of prismatic grains of clinopyroxene. During a first stage of weathering, the clinopyroxene has undergone incipient weathering. It has been partially replaced by a yellowish smectitic argiliplasma invading the crystal along the main transverse fractures. At a later stage, under conditions of weathering prevailing in the upper part of the profile, the pyroxene remnants become partially weathered to brown-colored iron-rich compounds, with formation of straight peripheral pores between the denticulate remnants and the newly formed material (inter-plasma - mineral pores). The iron oxyhydroxides produced by the weathering of the pyroxene also color the inner part of the domains of the smectitic secondary mineral. The general conditions of metamorphism are similar to those in the previous example. Note that the incipient metamorphism of the rock is also responsible for the formation of small inclusions of green hornblende within the prismatic crystals of clinopyroxene. These inclusions are much more resistant to weathering than are the pyroxene residues. Once the pyroxene remnants are completely weathered, the residues of hornblende would suggest (erroneously) the replacement of a prismatic crystal of hornblende by both smectitic and ferruginous materials.
LITHORELICS

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SOIL ON CLINOPYROXENITE
Middle part of the slope
Koua Bocca, Côte d'Ivoire
Depth: 0.6 m
Objective: x 2.5
PPL

461

SOIL ON CLINOPYROXENITE
Middle part of the slope
Koua Bocca, Côte d'Ivoire
Depth: 0.3 m
Objective: x 2.5
PPL

The first photograph shows a lithorelic exhibiting a poikilitic* texture. A large oikocryst* of greenish brown hornblende encloses many chadacrysts* of clinopyroxene and some grains of magnetite. All minerals of the lithorelic are unweathered, and its shape is irregular, not rounded, its margins following the previous intermineral boundaries of the rock-forming minerals. The lithorelic is partly surrounded by a dark brown clayey coating. Three well-rounded iron oxyhydroxide nodules are visible (A2–3, E 4) in the surrounding S-matrix. The second photograph shows another lithorelic that contains all the characteristic primary minerals of the ultrabasic rock. Many small crystals of well-cleaved clinopyroxene, some coarser-grained, poorly cleaved crystals of orthopyroxene (B5), a few crystals of olivine replaced by brownish “iddingsite”, and a few grains of magnetite, all are included in a poikiloblastic* pale brown hornblende. The lithorelic, whose external boundary follows the sinuous edge of the mineral grains, is embedded in a soil material that contains dark-colored clay material (D1), rounded nodules (A2), and detrital grains of quartz (E1). The S-matrix is separated from the lithorelic by a thick, empty, peripheral fissure. Grains of the three primary minerals were recently separated from the lithorelic (D2), whereas two more grains are already incorporated within the surrounding matrix (C2); they are now considered as isolated grains of the sand fraction of the soil.
This slightly weathered lithorelic is mainly composed of a large oikocryst* of hornblende in which pyroxene and magnetite are randomly distributed. The high resistance of both hornblende and magnetite to weathering explains the persistence of such a lithorelic within the alluvial deposits of the Tare River, which drains the ultramafic intrusion. Included grains of pyroxene are partly weathered to iron oxyhydroxides, which penetrate also the parallel cleavages of the hornblende host-crystal. A granostriated b-fabric is largely developed in the surrounding S-matrix.
Lithorelics of granitic origin containing many mineral grains: quartz, plagioclase converted to fine-grained white mica, microcline and hornblende. The lithorelic is embedded in a soil material; there, it is associated with many grains of detrital quartz and nodules of iron oxide. Note the peripheral open fissure, which continuously surrounds both lithorelic and nodule.
Alterorelics

Among all the types of alterorelics that can be observed in the soil horizons, alterorelics of allochthonous origin, which have been displaced either as lithorelics, or as mechanically resistant alterorelics, must be distinguished from the alterorelics of autochthonous origin, which are isolated residual fragments of an in situ alterite that has progressively been invaded and replaced by a newly formed plasma of pedological origin.

Allochthonous alterorelics

Alterorelics that were displaced alter their development as weathered units generally exhibit a rounded shape and a sharp border if they have survived the transport process. In contrast, alterorelics can still exhibit a sharply defined border and an angular outline if they are weathered after their transport and deposition as unweathered lithorelics. The alterorelics of the first type are relatively uncommon, whereas those of the second type can be very abundant within the near-surface covers located downslope of rock outcrops. This rather subtle distinction, which could seem rather pointless and academic, is commonly useful for chronological reconstruction of regional geomorphological events.

Alterorelics now observed as weathered entities within the upper horizons, after displacement and concentration as lithorelics, do not necessarily exhibit the same mineralogical composition nor the same microtextures as the in situ alterites within the lower levels of the profile. Alterorelics rich in iron hydroxide are predominant within the upper levels, whereas the normal weathering of the rock within the lower levels generally favors alteromorphs containing smectitic clays. The partly weathered alterorelics after coarse-grained minerals may exhibit both types of alteroplasmas (polyphase alteromorphs) if the primary residues, associated with the first-formed secondary mineral (e.g., smectite-group phase), have been subsequently weathered within the upper levels to other secondary products (e.g., oxides and hydroxides).

Lithorelics, which by definition consist only of unweathered fragments of rock, are mechanically very resistant to transport processes. Once redeposited, they may evolve in turn into brittle alterorelics that could quickly be destroyed, by dispersion of their clay content, if they were subsequently transported.

Lithorelics may become buried in thick covers of colluvium, where their further weathering may be very similar to that normally developed in the deep-seated alterites. Once completely weathered, their mineral content is commonly composed of smectite-rich and mechanically brittle argillite-alteroplasmas. This fact allows the soil scientist to determine that these alterorelics were originally displaced as unweathered solid lithorelics and not as brittle alterorelics. The slightest transport would necessarily destroy the latter by dispersing the clay content before deposition in a new environment. This assertion is all the more peremptory where the alterorelic is irregularly shaped, and exhibits important angular or protruding parts.

Not all alterorelics are so brittle. Some of them, by their mineral compositions or by their internal textures, may resist for long time despite lateral transport or vertical displacement. Among these resistant alterorelics, one can distinguish: (i) the relics altered under hypogene processes, which can be justly considered as lithorelics since their mineral constituents and their textures are already observed in the parent material of the pedological materials, (ii) the alterorelics that are protected by an epigenetic or accretion cortex, and (iii) those composed of ferruginous or gibbsite-rich crystalloplasmas, which are chemically stable, mechanically resistant, and disposed in septo-alteromorphs, such as can develop in alterites under ferrallitic conditions.

Autochthonous alterorelics

Alterorelics observed in soils do not always have an allochthonous origin. Most of them are maintained in situ, and without any displacement. This occurs by insulation of relict volumes of alterites within a pedological matrix formed relatively recently. The pedogenetic processes at work completely modify the inherited structures and textures of the alteroplasmas, replacing them by pedoplasmas whose mineral contents can differ quite significantly from those of the lower alterites.

The alterite is then replaced, along a network of fissures, by a neoplasma, generally more argillaceous, with which it contrasts strongly in color, porosity and microtexture. Digitate textures are progressively extended, widened, and interconnected; variously shaped and sized alterorelics are progressively individualized within this neoplasma, whose volume becomes more and more significant. The replacement seems to take place at a constant volume, and the alterorelics so created maintain, within the neoplasma, the position and orientation that they originally exhibited within the continuous alterite. The alterorelics are irregularly shaped or cavernous, with many embayments and
internal islands of pedoplasm. In addition, they are commonly strikingly fissured, and consequently are quickly reduced to an assemblage of smaller and smaller alterorelics.

Part of the iron content, which was originally homogeneously distributed within the isalterite, may be mobilized during contraction of the alterorelics. Iron is more and more concentrated in the residual parts of the alterite, and finally forms indurated cortices according to a process of peripheral and centripetal cortication (see below). Once a certain threshold is reached, the alterorelic is sufficiently enriched in iron to be indurated, which slows and ultimately stops its pedoplasmation. It forms a solid and resistant nodule, against which internal pressures operate. These pressures are progressively developed within a more and more abundant plasma. The pressures around the indurated nodules are ultimately expressed by the anisotropic reorientation of clay particles parallel to the walls of the resistant hard nodule (granostriated b-fabrics*). The reorientation of the plasma around the nodule may be responsible for further thickening of its indurated cortex.

Such horizons, composed of a continuous network of argillaceous neoplasma surrounding more or less indurated and displaced alterorelics, may be maintained for a long time in the upper levels of the old ferruginous or ferrallitic profiles. In such cases, the further cortication of the alterorelics and the further induration of the neoplasma, with the usual mineralogical and textural modifications, lead to the development of "pseudo-conglomeratic", "pseudo-gravel-bearing", "pseudo-pudding" or "pseudo-brecciated" iron crusts. In these, the visible features, in essence the previously formed alterorelics, usually strongly contrast, in color, shape and hardness, with the continuous and more homogeneous matrix that now cements them.

The autochthonous nature of such iron crusts can in some cases be proven by the continuity and uniformity of the structural features that appear in all alterorelics. The maintenance of original orientations is especially eloquent in the case of alterorelics formed at the expense of schists and other strongly foliated and lineated rocks.

Once these textures and compositions are acquired, both types of alterorelics, whatever their origin, autochthonous or allochthonous, exhibit similar patterns of behavior and further evolution.

Weathered grains of a mineral (alteromorphs) or polymineralic assemblages of weathered minerals (alterorelics) may persist for a long time in soil horizons or in superficial mantles. Persistence is favored where their texture is sufficiently resistant to internal movement such as creep, or where their chemical composition is closely in equilibrium with the geochemical conditions prevailing in these near-surface horizons. Iron-rich phanto-alteromorphs after biotite may persist in iron-rich crusts, whereas the less resistant quartz grains may be progressively alveolized and finally dissolved in such environments. In ferrallitic soils or even in vertisolic soils, alteromorphs may also persist without perceptible modification of their shape, texture or mineral composition.

**Pedorelics**

Pedorelics generally consist of compact, more or less indurated materials, such as papules*, miscellaneous concretions and fragments of crusts, especially if they have been transported. The state of their preservation depends, on the one hand, on their compactness and on their mechanical resistance to the processes that have promoted their release and displacement. On the other, it depends on their chemical and mineralogical compositions relative to the geochemical equilibrium prevailing in the environment of their deposition. The pedorelics form an important chapter of the micromorphology of soils sensu stricto. More information about them is very well presented in books on Pedology. The topic is not discussed further in this chapter, which focuses on the micromorphology of weathered minerals and alterorelics.
Depending on the properties of the horizon in which they are observed, lithorelics, and especially alterorelics, will face a miscellaneous array of fates. These include mechanical disaggregation resulting from physical processes, complete transformation of the weatherable minerals under the influence of chemical weathering, replacement of the previous compositions and textures by neoplasma under the influence of centripetal processes of replacement, and miscellaneous corifications under the influence of geochernoical processes of centrifugal accumulations.

**Physical Disaggregation**

**Process of disaggregation**

The internal movements of the pedoplasmas, the cyclic constraints of pressure, which varies according to the rhythm of the seasons, the internal process of erosion along pedotubules and other cracks, all these processes promote the gradual release of the mineral grains that are located at the periphery of the lithorelics, as well as those of the unweathered minerals of the alterorelics, by selective removal of the finest particles of the alteroplasmas. These mineral grains, released and isolated from their original assemblages, are gradually integrated into the pedoplasmas, in which they henceforth form a part of the skeleton units. These scattered minerals may be weatherable or unweatherable.

**Weatherability**

Not all primary minerals are easily reduced to isolated residual grains capable of persistence until the surficial horizon is attained. Very weatherable minerals, such as olivine- and pyroxene-group minerals, are commonly completely weathered in the lower part of the profiles. Thus they have little likelihood of persisting in an unweathered state in the upper horizons of soil. Only very active processes of erosion, acting on thin alterites, will promote a local increase in the proportion of such minerals in the soil horizons. Nevertheless, these minerals may occur if, at an early stage of hypogene alteration, they were surrounded by a protective layer of a resistant secondary mineral (e.g., amphibole, serpentinite, “iddingsite”), which protected them from further weathering. They are in this case “armored” grains. These very weatherable minerals may also be observed in the special case of andosols and alterites developed from deposits of recent volcanic ash. There, euhedral crystals of olivine and augite may be deposited together with particles of volcanic glass, and they may thus persist in an unweathered state for some time after their deposition.

The most commonly observed minerals to occur as isolated grains within the pedoplasmas are minerals of intermediate weatherability, such as members of the amphibole and epidote groups (of metamorphic or hydrothermal origins, usually), and the highly unweatherable minerals, of miscellaneous origin, such as quartz, tourmaline, rutile, zircon, staurolite, kyanite and, for some compositions, spinel and garnet. Directly derived from the disaggregation of the lithorelics, these minerals exhibit sizes, shapes and outlines comparable or very similar to those that they exhibited in the original rock.

In contrast, the weatherable minerals derived from the disaggregation of alterites and alterorelics are generally finer grained and exhibit shapes and outlines that they did not exhibit in the original rock. Their outlines are generally cavernous (feldspars) or denticulate (pyroxene, amphibole), their cleavages are emphasized (micas), their mechanical resistance has strongly decreased, and they disintegrate, contributing to the finer grain-sizes. Their particular shape, their habit, and the presence of traces of iron oxyhydroxides, and of alteroplasmas in the fissures, pores and cleavages, clearly distinguish them from the residual minerals directly derived by disaggregation of lithorelics or of unweathered parent rock (denticulate or cavernous residues versus cleaved or angular fragments).
Chemical Weathering

In most cases, the lithorelics are completely weathered before being disaggregated. The conditions of weathering being what they are in the upper horizons, the lithorelics are generally transformed into very porous and relatively iron-rich alterorelics (septo-alteromorphs), which contrast by their mineralogical composition and their texture with the smectite-rich alteromorphs (holo-alteromorphs) that can be encountered in the lower levels of the weathering profile.

In the alterorelics that still contain large residues of weatherable minerals, the respective influences of the successive episodes of weathering are expressed by the juxtaposition, in these residues, of two or more secondary products that normally do not coexist within alteromorphs.

Alterorelics after Pyroxenite

Composite "altero-lithorelics" after pyroxene-bearing rocks, originally composed of pyroxene-rich residues surrounded by their smectitic secondary products (formed in the lower levels of the profile), have their content of secondary minerals modified by the development of iron oxyhydroxides (formed by weathering of the remnants of pyroxene). These products rim the internal fringe of the banded network of smectite. This smectite finally disappears to give neoformed iron oxyhydroxides. The composite origin (pyroxene, smectite) of the two types of iron-rich secondary products is generally distinguished only with difficulty if no intermediate stages of weathering are available. In some cases, iron compounds directly derived from the pyroxene remnants, for example, exhibit a regular orientation of their optical features, which does not appear in the iron compounds derived from the later degradation of the smectite-bearing products.
ALTERORELIC OF ULTRABASIC ROCK
Koua Bocca, Côte d'Ivoire
Depth: 1.4 m
Objective: × 2.5
PPL and XPL

ALTERORELIC

of clinopyroxene, with most of the primary grains of clinopyroxene partially weathered to a smectitic clay in a phylloporo-alteromorph. All the particles of clay, which are formed from the same pyroxene grain, exhibit the same crystallographic direction, oriented parallel to the Z axis of the clinopyroxene. Small denticulate fragments of clinopyroxene are still embedded and visible in the clay-rich alteromorph (see the more detailed photomicrograph on the next page). During a later step of near-surface weathering, almost all remnants of clinopyroxene were weathered to iron oxyhydroxides, which now give the brownish color to the inner boundary of the smectitic secondary product. A few large crystals of clinopyroxene are very slightly weathered, and they appear as bright white patches under XPL. The thickness of the thin section is well below normal, which is why these highly birefringent minerals exhibit such low interference-colors here. The alterorelic is now embedded in a dark brown S-matrix, which shows important porosity and appreciable amounts of sand- and silt-sized grains of quartz and other resistant primary minerals. A peripheral fissure irregularly follows the outer limit of the alterorelic.
The third photomicrograph of the same alterorelic shows, at higher magnification, some textural and mineralogical details of the late stage of weathering of the alterorelic. During a first step of weathering, when the primary minerals were reached by the weathering front, the clinopyroxene grains were partially replaced by oriented argilliplasmas of smectite character. Many denticulate remnants of clinopyroxene were preserved within these argilliplasmas. As usually observed in similar cases, there is a strong relation in orientation between the denticulation of the remnants and the orientation of the secondary argilliplasma. The alterorelic, after having been isolated from the parent material and incorporated into the upper soil materials, has continued its weathering, but by a different process, which leads to the development of iron oxyhydroxides from the remnants of pyroxene. A thin brownish rim is formed around each denticulate remnant. Most original chemical elements are leached away, which determines the formation of an inter-plasma - mineral pore.

Part of the previously formed argilliplasmas are also colored by iron oxyhydroxides, derived from the weathering of pyroxene remnants. The brownish part of the argilliplasma is thus always contiguous to the denticulate remnants; it is not related, or very seldom so, to the original intermineral boundaries.
Lithorelic containing several grains of quartz surrounding a grain of feldspar (C2–3) that is partially weathered and replaced by deep brown iron oxyhydroxides. The grains, several of which exhibit the characteristic undulatory extinction of deformed quartz, are not chemically weathered, but several of them are fractured. The intermineral fissures and the intramineral cracks are filled by iron oxyhydroxides exhibiting a similar aspect and composition to those included in the feldspar grain. This pattern is due to an earlier episode of weathering, operating when the lithorelic was still embedded in soils of the upper part of the slope. The lithorelic, originating from granitic veins, has been transported along the slope, and it is now surrounded by smectitic material and detrital minerals that form the usual matrix of soils developed in the lower parts of the slope. In these lower parts, the original material is composed of detrital material originating from a mixture of weathered ultrabasic rocks and granitic rocks. The granitic rocks occur as veins or surround the ultrabasic intrusion.
The specimen contains large alterorelics of partly weathered ultrabasic rock, now mainly composed of crystals of tremolite formed at the expense of pyroxene, and very small interstitial grains of magnetite. The original texture is perfectly recognizable in most of the nucleus. All needles of tremolite are surrounded by a thin rim of iron oxyhydroxides forming a boxwork texture (septo-alteromorphs), in the cells of which denticulate remnants of tremolite are recognizable under XPL. Part of the nucleus is fringed by an irregular, more or less continuous area of compact iron oxyhydroxides (D2-4). This rim corresponds to the inner centripetal cortex formed by epigenetic replacement. The external part of the cortex, which is composed of alternating, concentric bands of goethite and hematite, arises by centrifugal accretion of material formed after the alteromorph has been deposited in the near-surface clay-rich matrix. A second similar nucleus, rimmed by another cortex, is just visible in the lower right corner of the photomicrograph. Small bridges connect the external parts of both rims, isolating small areas of dark S-matrix. The colorless areas in PPL (black areas under XPL) are pores originating from the erosion of the S-matrix in the interstitial parts of the iron crust that are not perfectly closed. Open concentric fissures are still visible in the part of the S-matrix that is trapped between the two adjacent cortices.
ALTERORELICS OF AN ULTRABASIC ROCK
Old ferrallitic soil
Koua Bocca, Côte d'Ivoire
Depth: 2 m
Objective: × 2.5
and × 1.6
PPL

LARGE FRAGMENTS of iron-enriched kaolinite-rich isalterite, divided into numerous smaller alterorelics, isolated within a reddish brown pedoplasma. The pedoplasma irregularly invades and replaces the isalterite along numerous reticular fissures. Several fissures are more recently formed, and not yet surrounded by the reddish brown pedoplasma. The alterorelics are progressively replaced along more and more numerous fissures, and their size decreases regularly from right to left. In the left part of the upper photomicrograph, the texture of the isalterite has completely disappeared. A detailed study, at a higher magnification, shows that most of the open fissures are coated by a clay-rich material whose grain size is much smaller than that of the first-formed pedoplasma. The lower photomicrograph, taken from the same sample, shows that the alterorelic is progressively replaced, in situ, by the pedoplasma without disturbing the original orientation of the isalterite. All fragments of the isalterite have maintained their original orientation, and the distance between the center of all these fragments has not been modified during the replacement of the dark brown isalterite by the secondary red pedoplasma. The replacement takes place in situ by an isovolumetric process.
A view of the contact area among four alterorelics and their surrounding reddish brown pedoplasma, at a level in the profile in which slight induration has occurred. The profile is the same as that of the earlier photographs. A goethite-rich cortex is observed around the upper alterorelic; that cortex is developed by epigenetic replacement at the expense of the alterorelic itself. This first-formed indurated part acts as a resistant body against which the internal stress-related movements within the surrounding plasma and regular peripheral open fissures around each of these hard nodules are developed. The contraction of the plasma is also expressed by the formation of interconnected, more or less radial fissures, along which thin clay-rich deposits are observed.

At this higher level of the profile, the alterorelics begin to be slowly displaced by internal creep, and the pedoplasmas now contain some detrital grains of quartz (which do not appear within the alterorelics). At a more advanced stage, the individual cortex will become thicker and thicker, not only by the development of the inner cortices, but also by the formation of external microlaminated cortices. Finally, the red plasma itself will be replaced by in situ deposits of hematite and goethite, and a hard iron crust will be formed (not shown) if external processes of erosion allow its development.
Both photographs were taken in the same profile, developed on volcano-sedimentary rocks, but at different depths along the profile. The first one, which corresponds to the deeper sample, shows the formation and the individualization of alterorelics after the development of a pedological S-matrix formed at the expense of the isalterite. In the deeper horizons (not shown), the isalterite is continuous, and exhibits, in all its parts, the constant orientation of the sedimentary rock; a few meters above, the alterite is fragmented by increasingly numerous and thicker fissures, along which the pedoplasma develops at the expense of the margins of the fragmented residues of alterite. These residues progressively develop a more and more rounded shape, and they are separated from each other by wider and wider volumes of pedoplasma. This results in the formation of islands of isalterite which, ultimately, undergo displacement under the influence of their creep down the slope. Several alterorelics of different sizes, shapes and orientations are shown in this first photograph. In the second one, the alterorelics have taken on a more and more rounded shape, whereas incipient induration affects their external part. The partial induration of the margins results in their partial opacity and in the formation of a continuous peripheral fissure. The pedoplasma of the first sample is soft, whereas the pedoplasma that surrounds the alterorelic in the second photograph is slightly indurated. A hard iron crust (not shown) is formed at the top of the profile.
This photograph shows the differential behavior of the physical and pedogenetic processes operating in argillaceous and unindurated materials that surround diversely indurated relict nodules. In the central area of the photograph, a reddish brown argillaceous material represents the general matrix of the colluvial horizon situated on the upper part of a deeply weathered profile. To the right, an indurated compact nodule, formed at the expense of an alterorelic of ultrabasic rock, is completely indurated and very resistant to the evolutionary processes. A peripheral fissure is formed in the contact area between the hard and the soft materials, and no internal fissures or cracks appear within the nodule. This nodule has been inherited from an old and indurated ferrallitic horizon that caps the top of the slope. This nodule is similar to that shown in photographs 493 and 494, for example. To the left, an unindurated alterorelic, similar to the alterorelics shown in photographs 473 and 474, is directly inherited from the deeply weathered, saliteritic or alloteritic horizons of the profiles at the upper part of the slope. The alterorelic is largely impregnated by dark red hematite-rich material, but it is not indurated. The internal movements of the horizons along the slope and the pedogenetic processes that are operating in this material are responsible for the important development of fissures in the soft alterorelic and for the replacement of its inherited material by secondary plasmas of similar mineralogical composition and textural appearance as in the surrounding matrix. The alterorelic is divided into numerous fragments, whose volumes progressively decrease. The textural inheritance of the alterorelic, more or less preserved during the first (saliteritic) and the second (alloteritic) processes of weathering, is now definitively lost.
ALTERORELICS

OF GNEISSIC CALC-ALKALINE GRANITE
Akoukro, Dimbokro, Côte d'Ivoire
Depth: 1.8 m
Objective: x 6.3
PPL

Many interconnected fissures, coated by yellowish clay-rich material, cut a large alterorelic originating from the weathering of a mica-rich layer of a gneissic calc-alkaline granite. The clay minerals originating from the weathering of the feldspars are now recognizable only with difficulty because they have become preferentially iron-stained and, more recently, cut by the network of irregular fissures. In contrast, the large crystals of kaolinite, originating from the weathering of the original crystals of biotite via an intermediate step of vermiculite formation, are much better preserved. Traces of the previous expansions during the two stages of weathering are quite visible in all macrocrystals of iron-stained kaolinite, whose shape, cleavage and parallel intraminal fissures are characteristic of the meso-alteromorphs formed by weathering of the mica. A quartz grain is just visible in the left lower part of the photograph (B5). The replacement process, which here promotes the disaggregation of this alterite, is similar to the process which, in the previous illustrations, progressively destroys the continuously textured isaltered. The difference lies in the fact that here, the division of the alterite operates preferentially by the opening of interconnected fissures within the fine clay material, whereas the relatively coarse alteromorphs of kaolinite are avoided on the short term.
Iron crust on glimmerite
Koua Bocca, Côte d’Ivoire
Sampled at soil surface
Objective: × 4
PPL and XPL

This iron crust is developed at the expense of glimmerite, a biotite-rich rock that is locally developed, in the Koua Bocca ultramafic intrusion, in the contact areas with the surrounding younger granite. Most of the original texture of this metasomatic rock was obscured during the successive stages of weathering and during the stage of induration by iron oxyhydroxides as a result of replacement. Nevertheless, some phanto-alteromorphs after biotite and vermiculite are still identifiable in this iron crust owing to the persistence of their original layered structure, which was well preserved during the formation of secondary goethite. Internal, irregular, dark red areas are composed of old hematite-rich, ferrallitic alteropedoplasmas, whose precursor, pyroxene or feldspar, or whose alloogenic origin, cannot be clearly identified. Many large empty pores are randomly distributed in the iron crust, but most of them seem to be preferentially associated with the red-colored areas of pedoplasma. Note the good crystallinity of the microparticles of goethite, mainly at the margins of each kaolinite mesoalteromorph.
ILLUSTRATE a monomineralic grain of quartz embedded in hard iron crust. The mineral seems very strongly corroded by slow dissolution. Its originally smooth and elliptical shape is now converted to a very dissected one, with numerous irregular or digitate embayments (better visible under XPL), partly infilled by iron oxyhydroxides. Inner islands of dissolved material, which seem isolated in the plane of the thin section, are certainly linked in the third dimension to other embayments.
ALTERORELICS

RESIDUAL MINERAL GRAIN
Old ferrallitic soil on upper part of the slope
Koua Bocca, Côte d'Ivoire
Depth: 1.2 m
Objective: x 4
PPL and XPL

A large grain of partially "iddingsitized" olivine. Most of the grain has been replaced by compact and homogeneous "iddingsite" (C1, D3), whereas a residual part of the olivine crystal was cut by an irregular network of banded "iddingsite" running along some of the original protoclastic fractures (D1–2, D5). Some isolated and unaltered remnants of olivine were maintained on the short term within the banded network of "iddingsite". During a later stage of weathering, these remnants were transformed to a thin rim of iron oxyhydroxides, which coat the bands of "iddingsite" and which surround residual empty pores, simulating a boxwork structure. During this stage of weathering, the previously formed "iddingsite" component has had all but its iron oxide content leached away; as a result, the "iddingsite" alteromorph was replaced by a ferruginous alteromorph, which maintains all the previously inherited textural features. This alterorelic is now associated with many other pedo-, altero- and lithorelics (not shown in the photograph).
Residual mineral grain
Intermediate slope
Colluvial soil
Koua Bocca, Côte d'Ivoire
Depth: 1 m
Objective: × 2.5
PPL and XPL

This residual grain of weathered biotite—vermiculite—kaolinite was further replaced by dark brown iron oxyhydroxides. The phylloporo-alteromorph aspect of the meso-alteromorph has been well preserved during the successive stages of weathering. Its partial induration by the ferruginous components has allowed the alteromorph to survive its transport and deposition. The characteristic internal phyllo-pores of the alteromorphs after micaceous minerals, which invariably expand greatly perpendicular to their sheet structure, is clearly visible in the photomicrograph taken under PPL. Under XPL, two other features are recognizable. Firstly, some of the phyllo-pores have been infilled with quartz, individual crystals of which grow perpendicularly to the layers of the sheets. Secondly, the two opposite margins of the alteromorph, which are oriented perpendicularly to the sheets, are partly replaced by a new generation of iron oxyhydroxides that obliterate the previously preserved traces of the sheet structure of the micaceous minerals. The margins that are parallel to the sheet structure are not rimmed by the new generation of deposits, and seem to be more resistant to the replacement.
CENTRIPETAL CORTIFICATION

Process of induration and textural evolution

After the first stage of weathering, or concurrently with it, a cortification of the alterorelic may develop in a centripetal manner. Compounds of iron, generally goethite, completely replace the entire alterorelic, pores included. The alterorelic is gradually rendered more and more compact and hard as the boxworks and porous textures formed by weathering are obscured and destroyed, first along its periphery, then throughout the alterorelic.

This first centripetal process of internal cortification results in a compact, homogeneous and generally untextured hard material. The textures inherited from the primary minerals, which have been more or less maintained in the alteromorphs, are definitively lost. In this way, the textured and recognizable alteromorphs are replaced by indurated and untextured nodules, whose origin becomes less and less identifiable. Alteromorphs of different petrological origin can, as a result, be replaced by very similar nodules without any unique distinguishing criterion. Only the ephemeral occurrence of quartz grains or of other resistant minerals allows the most important groups of rock to be distinguished from one another.

This first cortification is internal with respect to the border of the alterorelic, and it progresses in a centripetal manner. No volume increase is expected to be perceptible at the scale of the optical microscope. The progressive replacement of the weathered minerals and residual voids by a compact and undifferentiated matrix promotes the disappearance of the inherited textures, which are completely obliterated and definitively lost. The apparent density of the alterorelic has greatly increased.

Persistent minerals within areas of cortification

Only specific primary or secondary minerals, whose composition is more closely in equilibrium with the new geochemical conditions prevailing in the upper horizons, can resist this centripetal process of cortification; the inherited textures are thus partly maintained. These resistant primary minerals form protruding parts or isolated islands within the areas entirely transformed by the process of cortification.

In ultramafic rocks, for example, residual areas of "iddingsite" previously formed by hypogene alteration of the olivine-group mineral, or residual grains of hematite formed by replacement of the original crystals of magnetite, are common within alterorelics that are completely replaced by iron oxyhydroxides.

Polymineralic or isolated grains of quartz also can resist the processes of weathering but, now included within the iron-rich environments of the newly formed cortices, they progressively disappear by breakage, alveolization and dissolution. They leave, within the ferruginous nodules, only irregular pores whose size and shape correspond to those of the original grains. It is noteworthy that the dissolution of the quartz grains begins much later than cortification. Once formed, the late pores, which are well isolated within the nodule or within its cortex, are not infilled by further accumulations of iron oxyhydroxides, and remain empty.

Some secondary silicates can also, at least temporarily, resist complete transformation to ferruginous products. Such is the case of some pedocrites and alteromorphs that are composed of macrocrystalline kaolinite after micas or after vermiculite. Although only partly replaced by goethite, they are perfectly recognizable as phano-alteromorphs. If these chemically resistant grains are located near the border of the alterorelic, they form outward-protruding parts within the peripheral cortex. In thin section, the cortex appears as a discontinuous concentric banded area.

Relics of materials of organic origin, such as fragments of charcoal, also can experience at least partial internal cortification. The unaffected nucleus then clearly maintains the cellular texture of the original organic material.

Iron-rich secondary minerals andalteromorphs also can resist subsequent alteration, either because of their original composition (as in the case of "iddingsite"), or because of their late replacement in a new environment (as for example iron-rich alteromorphs of kaolinite after biotite). Although they are isolated as residual minerals, they behave as polymineralic alteromorphs.
Whether entirely or partly replaced, the alterorelic has its size preserved by this first process of cortification. No perceptible modifications in volume are observed at the optical scale. The process of internal cortification invades the alterorelic in an essentially centripetal way and produces iron-rich indurated nodules. The internal cortification destroys the detail of the pre-existing texture of the alteromorph.

**Pedoplasmaton of the residual textures**

In environments in which absolute accumulation of iron is reduced or nonexistent, or where ferruginous alterorelics are in geochemical disequilibrium, an inverse phenomenon may be observed. There is no longer peripheral centripetal cortification, but rather progressive and gradual replacement of the residual textures by silicate-based pedoplasmas. The alterorelic then becomes abundantly fissured, domains are divided, and their volumes progressively decrease. A pedoplasma appears that is similar to the surrounding pedoplasma, except that it may temporarily maintain, within the original perimeter of the alterorelic, some portion of its more resistant minerals. The nuclei and cortices that were developed during a previous step, or within another environment, may be in disequilibrium with the surrounding matrix. Under these conditions, they are gradually exfoliated and divided into many fragments that are soon integrated into the surrounding plasmas. Concentric fissures may also develop within the cortices, and also within the nucleus itself. Combined with radially arranged fissures, they give way to isolation of polyhedral fragments, which are quickly displaced or integrated.
Photomicrographs focus on the intermediate areas, which distinctly show the three main steps in the formation of the actual alterorelic. The central part of the nucleus, whose original texture is preserved, is composed of a cryptomorphic assemblage of alterorelics after clinopyroxene, in which all primary grains were weathered to a very porous boxwork of goethite. Small grains of magnetite are still visible. The nucleus of the alteromorph is irregularly rimmed by a first internal cortex, formed by a replacement process that promoted the recrystallization of the goethite-rich septa of the alteromorphs and the disappearance of their secondary pores by infilling by goethite. This epigenetic replacement process gave rise to compact, nonporous areas in which some small relics of alteromorphs are maintained. This first internal cortex is then surrounded by a further external complex cortex formed by accretion of a secondary coating of goethite (yellow undulating bands) alternating with discontinuous and irregular red-colored scales originating from the incorporation of pedoplasma material. Remnants of the original pedoplasma, with large pores, are visible in a corner of each photomicrograph.
**CENTRIPETAL CORIFICATION**

**491**

**ALTERORELIC AFTER ULTRABASIC IGNEOUS ROCK**
Old ferrallitic red soil
Koua Bocca, Côte d'Ivoire
Depth: 2 m
Objective: × 1.6
PPL

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**492**

**ALTERORELIC AFTER ULTRABASIC ROCK**
Old ferrallitic red soil
Koua Bocca, Côte d'Ivoire
Depth: 2 m
Objective: × 2.5
PPL

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The upper photograph shows a very advanced stage in the replacement of the nucleus of an alteromorph by a very compact inner cortex formed by a centripetal replacement process that promoted the formation of homogeneously textured areas replacing most of the nucleus. Some grains of magnetite and some very porous islands of the original septo-alteromorphs are temporarily preserved in this area. Irregular patches of dark brown material, contrasting with the general yellowish color of the nodule, are traces of completely resorbed alteromorphs; they are phanto-alteromorphs. The persistence of such internal textural features shows that this nodule is a replaced alterorelic. The hardness of the nodule, compared to the softness of the surrounding pedoplasma, is such that a regular peripheral fissure completely surrounds the alterorelic.

The lower photograph, taken at higher magnification, shows part of a somewhat similar alterorelic in which most of the components were replaced by a secondary accumulation of goethite. Only some small grains of magnetite and some islands of alterorelics are still visible in this compact nodule, but these small remnants are sufficiently characteristic features to prove the ultramafic origin of the alterorelic.
**Porous Nodule**

Superficial soil  
Koua Bocca, Côte d'Ivoire  
Depth: 1.2 m  
Objective: × 1.6  
PPL and XPL

**Description:**

Rounded nodule of compact iron oxyhydroxides containing many small irregular empty pores. In contrast to the primary or secondary iron oxide (magnetite) that is in equilibrium with the newly formed internal cortex, the quartz grains are slowly dissolved in such a material. Residual pores are formed whose shape corresponds to the shape of the grains removed. Although no residual quartz is visible in this concretion, it seems highly probable that these pores correspond to voids formed by the dissolution of quartz grains. Note, in the photograph taken in XPL, the similarity of the indurated goethite-rich material to the corresponding material of the two previous photographs.
ALTERORELIC AFTER OLIVINE-BEARING ROCK
included in an iron crust
Koua Bocca, Côte d'Ivoire
Sampled at soil surface
Objective: x 4
PPL

Detailed view of the internal centripetal cortex formed by an epigenetic process at the expense of a part of a nucleus composed of many weathered minerals. The original texture is easily recognizable in the lower part of the nucleus, whereas in its upper part, all septoalteromorphs after pyroxene have been obscured by the replacement process, giving rise to a homogeneous compact goethite-rich area. Only resistant primary (magnetite) and secondary ("iddingsite") minerals, which are in closer geochemical equilibrium with the ferruginous portion, are well preserved and appear as isolated remnants within the more homogeneous goethite-rich matrix. The external dark red plasma is indurated by hematite, which leads to a hard iron crust. The large grain of "iddingsite" after olivine, which is now converted to goethite by the leaching of its silicate components, still exhibits the inherited, homogeneously well-oriented pattern of the original "iddingsite", as well as the network of protoclastic fractures that is very characteristic of the original crystal of olivine. The "iddingsite" grain strongly protrudes into the cortex. This latter feature shows that the goethite cortex was formed at the expense of the alterorelic, avoiding the "iddingsite" and magnetite grains, and not at the expense of the surrounding matrix in which the alterorelic is now embedded. It shows also that this cortex was formed at an earlier stage, before the deposition of the alterorelic in the matrix. Were it not so, the protruding very brittle grain of "iddingsite" certainly would have been eroded during the transport of the alterorelic. This chronology is also strengthened by the fact that the goethite-rich cortex seems to have been partly eroded during its displacement, as well as the included grain of "iddingsite". In its external part, it exhibits a curved smooth outline, in continuity with the similar habit of the external shape of the cortex. In conclusion, the chronological evolution of the lithorelic, as can be deduced from careful micromorphological observations and from the logical deductions that they involve, is reconstituted as follows: a) formation of an alterorelic exhibiting a larger size than that now exhibited, b) formation of the epigenetic cortex preserving an important part of the nucleus and also some isolated grains of magnetite and a large "iddingsite" pseudomorph, c) displacement of the alteromorph, with partial peripheral erosion, which promotes the formation of a smoothly rounded shape along both goethite-rich cortex and protruding "iddingsite", and d) deposition of the complex nodule in a S-matrix, later indurated to an iron crust. The goethite-rich centripetal cortex probably formed continuously at the expense of the alterorelic during the last steps and even after the last one.
Sampled at soil surface

Objective: x 4
PPL and XPL

composed mainly of a grain of goethite originating from the late evolution of a grain of "iddingsite" after olivine. The "iddingsite" grain is accompanied by a few remnants of alteromorphs after clinopyroxene and by small grains of magnetite. The alterorelic is now surrounded by a complex accreted cortex whose color and mineralogical composition vary and alternate from the center to the external boundary. Most of the surrounding pedoplasma is also indurated, mainly by hematite-dominant microcrystalline material. In the upper left corner of the photograph, the more external cortex of the main nodule forms a bridge with the corresponding external cortex of a neighboring nodule. Both nodules are now linked and, in the central part of the bridge area, a residual pore is formed following the later dissolution of a grain of detrital quartz. In the upper right corner, an elliptical area of goethite, completely embedded within a triangular area of hematite, corresponds to a "polar" cut in the external part of the cortex of another nodule that is not included in the thickness of the thin section. A still undisturbed and porous area of pedoplasma is visible in the lower right part of the photograph. It is noteworthy that the main micromorphological features of the "iddingsite" grain were perfectly maintained during all stages of evolution of the nodule: homogeneous crystallographic orientation (as seen in XPL) and the network of the protoelastic fractures that is a characteristic feature of all the precursor crystals of olivine observed in the Koua Bocca ultramafic intrusion.
ALTERORELIC AFTER ULTRABASIC ROCK
Koua Bocca, Côte d'Ivoire
Depth: 0.4 m
Objective: × 6.3
PPL

This photograph offers a detailed view of an alterorelic after an ultrabasic rock in which the opaque grains of primary magnetite and the crypto-alteromorphs after grains of pyroxene are easily recognizable. Parts of the alteromorphs, in the external part of the alterorelic, were replaced by yellowish orange goethite. The original secondary pores have disappeared in this first cortex, whereas in the central area of the alterorelic, this pore space is still preserved. This first step of replacement by goethite was then followed by the formation of an undulating microlaminated cortex, formed by accretion at the expense of the surrounding pedo-plasma; such accumulation cortices give to the alterorelic a progressively smoother external shape as the thickening of the external cortex continues. This first microlaminated cortex is then followed by the more irregular accretion of external scales of plasma, which appear as red hematite-dominant bands alternating with the yellow goethite-dominant ones. The process responsible for the alternation of yellow and red bands arises as follows. Where the peripheral fissure closely surrounds the previously formed lamina of the cortex, the precipitation of crystallites of goethite occurs on top of this last lamina. The thickening of the cortex appears to be continuous, and the microlamination of the cortex of goethite is only due to the successive deposits of pure goethite. But it may happen that the peripheral fissure does not exactly follow the last-formed lamina of goethite. The fissure then produces a crescentic or a more or less thick shell of the surrounding plasma material, strongly bound to the cortex. The next deposit of goethite will coat these crescents and shells, and the now isolated part of the plasma will later be replaced by hematite. The microporosity of these shells of plasma is much smaller than the open porosity of the peripheral fissure; anhydrous iron oxide (hematite) is then preferentially formed in the plasma-rich shells, whereas the hydroxide (goethite) is formed along the fissure.
The lower photograph shows an irregular alteration, most of which is composed of a large grain of magnetite including, in its external border, some phano-alteromorphs after pyroxene and, in its central part, some small inclusions of now weathered green pleonaste (spinel). These magnetite and pleonaste cumulates have formed in the lower part of the ultrabasic intrusion, and they are consequently very widespread in all weathering profiles and iron crusts of the Koua Bocca.

The lower photograph shows a highly fractured grain of detrital quartz originating from a quartz vein. In the old ferrallitic soils and iron crusts, quartz grains are weatherable minerals. After a first stage of breaking, they are slowly dissolved along their cracks, leaving open intramineral fissures that are quickly infilled by brownish deposits of iron oxhydroxides. The quartz grain shown here is slightly weathered along its internal microcracks. It is regularly surrounded by a thin continuous peripheral fissure, as is typical of all rigid bodies in this clay-rich material, the peripheral fissure is interconnected with a network of radially ordered fissures. The quartz grain was obviously subjected to transport over a long distance, as is proved by its rounded shape and by the preservation, within a deep embayment, of a small part of a previously formed concentric cortex (B2).
LARGE PEDORELIC red papule (C3) whose internal fabric is formed by microlaminated clay infillings of a now-obliterated previous void. Before its incorporation into the iron crust, the microlaminated clay coatings were concentrically fissured, partially dissolved and subsequently replaced by yellow goethite and black manganese deposits (C2, C4). This complex pedorelic is still embedded in its original isalteritic matrix, which is still recognizable in spite of the fact that most of it has been replaced by a goethite-dominant matrix. The papule and its surrounding replaced matrix were later transported, which results in the well-rounded shape of the nodule. This first cortex has later been surrounded by a more recent concentric cortex, whose alternating red- and yellow-colored laminae are clearly seen. The more external laminae of the last cortex are bridged to the corresponding laminae of the neighboring nodules. A very porous iron crust results in which residual, unindurated and porous volumes of plasma (D1, E3) are isolated in the closed spaces, entirely surrounded by the interconnected cortices.
Charcoal fragments are frequently observed in the upper horizons of tropical soils, mainly in the savannah regions, where the vegetal cover is regularly burned. Burned vegetal fragments are regularly incorporated into the soil material, in which they can constitute an appreciable part of the coarse and sandy fractions. These organic structures can resist pedogenic and geomorphological processes for a long time. They can survive transport processes and be rounded just like grains of detrital minerals. The photographs show a well-rounded elliptical fragment of charcoal which, after a stage of transport responsible for its roundness, has been buried to a depth of half a meter. The organic texture is very well preserved, and the origin of the fragment could certainly be identified by a soil scientist specializing in the determination of plant residues. Note that as in the case of the harder grains of detrital minerals, the plant residue is well rounded, is rimmed by an internal halo of impregnated iron oxyhydroxides (dark brown in XPL), and is surrounded by an external cortex of goethite formed by accretion at the expense of the surrounding matrix. The internal fabric is perfectly maintained, although the original organic material has been partly replaced by iron hydroxides (yellow cellular structure under XPL).
Process of development of the peripheral stress cutans

Alterorelics completely replaced by ferruginous material according to the process described above, and alterorelics that maintain internal textures, give way to indurated nodules that are subjected to pressure constraints owing to the swelling of the internodular plasma and to the higher quantities of circulating water around each impermeable nodule. The pressure is not isotropically distributed, and is not the same as the hydrostatic pressure. It is largely directed and highest nearest the margins of the hard and incompressible nodules. Such pressure is responsible for the tangential orientation of the particles of plasma with respect to the periphery of these nodules. These pressurized areas are expressed in thin section and under crossed polarizers as a strongly birefringent halo, which contrasts, by the preferred orientation of its constituents, with the unoriented plasma of the surrounding matrix. Such halos form areas of granostriated b-fabric* (or stress cutans*), which are only recognizable under crossed polarizers. These areas of granostriated b-fabric are particularly well developed within the areas caught between two closely spaced nodules.

It is obvious that this process can be effective only within the argilliplasmas, mainly the smectite-bearing plasmas, and that it becomes ineffective within the virtually inert sandy horizons. There, alternating variations of humidity and dryness do not produce any variations in pressure and volume. As a result of shrinkage, as during the dry season, a circum-nodular fissure is developed around the nodule, along which it is separated from the surrounding matrix.

In nodule-rich horizons, the internodular plasmas become completely oriented. The circum-nodular fissure is no longer so regular; instead, it veers away from the nodules, and tends to develop preferentially in the central parts of areas of plasma, which are torn to pieces and whose fragments are attached to neighboring nodules, simulating in this manner a "chitonic distribution pattern"* (Stoops & Jongerius 1975).

If the volume of the plasma decreases to such an extent that the nodules are very closely spaced, the volumes of plasma are reduced to bridges or intertextic* branches, which link neighboring nodules. A threshold also is reached when the nodules become numerous and joined, and when the volume of the interstitial argillaceous matrix is consequently rendered insufficient for differential changes in volume to be recorded within it.

Development of an accretion cortex

In contrast, during periods of dryness, desiccation promotes the development of open, peripheral, circum-nodular fissures, which faithfully follow the margins of the alterorelics or nodules and their cortices. Some irregularities may appear fortuitously during repeated alternation of swelling and shrinkage. The peripheral fissure, instead of regularly following the cortex, may penetrate into it and isolate fragments, which are soon incorporated into the surrounding matrix. In contrast, the fissure may progress away from the cortex and incorporate into the nodule small portions of the surrounding matrix. These isolated volumes of plasma, which are further incorporated into the cortex by later superposition of new laminae of goethite, are expressed as hematite-rich intercalations which, by their red color, contrast strongly with the homogeneous bright yellow color of the goethite-rich replacement and accretion cortices.

T}hese pressure-induced cutans (stress cutans*), developed around each nodule, account for a second ferruginous cortex, which forms, this time, by a centrifugal process. The microlayer of reoriented plasma that surrounds the nodule and that adheres strongly to it is replaced by goethite. This hard and geochemically stable neoformed microlayer is, in this way, incorporated into the nodule. Each newly formed lamina of the cortex attaches itself to the previous one; as a result, the total volume of the nodule progressively increases.

The next period of desiccation promotes the opening of a new peripheral fissure, or contraction crack, which completely envelops the outermost (the most recent) lamina of the cortex and promotes the opening of radial and interconnected intraplasmatic pores. This opening allows, by the continuity of its network, circulation of water and the deposition of illuvial material derived from the upper horizons. As soon as the rains resume, but before the pores become closed by the general swelling of the pedoplasmas, this peripheral contraction-induced pore-space is infilled with new illuviations or more precipitations of iron oxyhydroxides. These contribute, by their presence, to
an increase in internal pressure on the neoplasma once the humid period resumes. The illuviation cutans in the peripheral pores rest against the last-formed microlamina of the cortex, become impregnated with iron oxyhydroxides, are indurated, and so contribute to the progressive thickening of the cortex, which is, at least in part, developed at the expense of the surrounding pedoplasma. Without these external transfers, it is highly likely that the cortification would stop quickly, because the quantity of internodular plasma would not be sufficient to respond to the variations in internal pressure and to support further stress cutans.

These areas of higher pressure are not uniformly or continuously distributed around the lithorelics. They are expected to be thicker in embayments and thinner against the protruding parts of the alterorelic. In this way, the successive microlaminae of the cortex tend to progressively subdue the irregularities of the nodule margins. This tendency explains the increasingly regular and smoother cortices, whose external margin becomes more and more circular or elliptical. After a sufficiently long period of time, alterorelics with a subcircular, square or triangular section can thus acquire a quasi-perfect circular shape.

**Mineral content of the accretion cortex**

Grains of resistant minerals, such as magnetite and "iddingsite", which may have survived in the first-formed epigenetic replacement cortex, are not observed in the accretion cortex. This observation proves that the accretion is developed at the expense of the surrounding plasmas, and not at the expense of the alterorelic itself. The accretion cortex is generally composed of very thin concentric layers of yellow goethite, in which continuous or discontinuous (crescent-shaped) layers of red hematite-rich plasma are in some cases intercalated. These intercalations originate from the local integration of parts of the internodular pedoplasma.

In contrast, the accretion cortices can incorporate skeleton units, mainly quartz grains, that belong to the surrounding matrix, and that have an ultimate origin very different from that of the indurated alteromorphs. These grains are progressively trapped and incorporated into the successive microlaminae of the cortex. In disequilibrium with the iron-rich environment of the surrounding cortex, these quartz grains commonly are later completely dissolved; this leaves empty pores whose shapes are the only evidence of their former presence. Their distribution in the cortex, and the fact that the elongate residual pores commonly are oriented tangentially to the cortex lineation, prove the existence of confining pressures around the alterorelics and, consequently, the formation of the cortex at the expense of the pedoplasma.

The distinction between the nucleus, which results from the epigenetic replacement of the alterorelic, and the accretion cortex, which results from the incorporation of peripheral pedoplasma, is relatively easy in the case of nodules derived from alterorelics developed at the expense of basic or ultrabasic rocks. The ferruginous nucleus is compact and homogeneous, whereas the surrounding cortex can contain skeleton grains of quartz originating from the surrounding pedoplasmas, whose origin is generally more heterogeneous.

In contrast, in landscapes developed over a granitic basement, this distinction becomes difficult, because the skeleton grains, mainly quartz, are much more abundant, and present within both alterorelics and pedoplasmas. These skeleton grains are thus observed in comparable quantities in both nuclei and cortices. Owing to the abundance of the skeleton elements and the relative impoverishment of available ferruginous argilliplasmas, these nuclei exhibit poorly developed concentric microtextures of cortification, which are indistinct and identifiable only with difficulty. In soils developed at the expense of granitic rocks, the abundance of the ubiquitous quartz grains within both nuclei and poorly developed cortices does not always allow the clear and unequivocal distinction between allochthonous cortified alterorelics and orthic concretions formed in situ.
NODULES AND S-MATRIX
in a soil developed at an intermediate level of a slope
Koua Bocca, Côte d'Ivoire
Depth: 0.8 m
Objective: x 2.5
PPL and XPL

TWO WELL-BONDED nodules are embedded in a smectite-rich argillaceous S-matrix of a soil developed on ultrabasic rock at an intermediate level of a slope. The matrix contains few grains of detrital quartz and rare remnants of heavy minerals. This horizon contains numerous nodules of various origin, but the nuclei formed at the expense of ultrabasic rocks are more numerous than those formed at the expense of granite. Lithorelics of quartz and microgranite veins, with or without surrounding cortex, are very abundant. All the nodules (and all the largest lithorelics, not shown) are regularly surrounded by a well-developed granostriated birefringence-fabrics, as shown in the lower photomicrograph (XPL). The granostriation of the S-matrix is much more widely developed in the volumes that are located between two adjacent nodules, and mainly where the distance between them is the shortest (B3-4). It develops only very slightly, or not at all, around the small grains of detrital minerals. Peripheral fissures are not very visible, and they exhibit, where present, an irregular pattern of distribution (B-C 1-2).
In these parts of the horizon in which the nodules are very abundant and the volume of the S-matrix is as a result much less important, the granostriated birefringence-fabric may extend to all parts of the matrix, as shown in these photomicrographs. In this case, the peripheral fissures usually observed, which normally follow the external margin of the nodules, are replaced by irregular interstitial fissures and elongate pores located within the matrix itself, at somewhat equal distances between neighboring nodules, where the matrix is less compact. The volume of the interstitial matrix is then equally divided between the adjacent nodules. The related distribution of coarse and fine constituents is somewhat similar, at a larger scale, to the chytic distribution usually observed in soils in which the coarser units are surrounded by a rim of smaller units (Stoops & Jongerius 1975).
NODULES AND S-MATRIX
in a soil developed at an intermediate level of a slope
Koua Bocca, Côte d'Ivoire
Depth: 1 m
Objective: × 2.5
PPL and XPL

The further development of the interstitial fissures and pores, whose early stages of formation is illustrated in the previous photomicrographs, results in the appearance of large irregular pores, principally distributed in the widest volumes of matrix. This preferentially distributed internal erosion results in the preservation of the compacted parts of the matrix located in the narrow spaces between adjacent nodules. The nodules are finally joined together by braces of relict S-matrix, with simulation of a gefuric distribution (Stoops & Jongerius 1975). The resulting texture also exhibits some similarity to the textures observed in some of the iron crusts to be described later (see photomicrographs 548 and 549, for example). If one imagines a replacement of the irregular interstitial pores by more rounded and smoother ones, and a hardening of the braces by ferruginous impregnations, the similarity between the two textures will become very apparent.
CORTIFIED NODULES
at an intermediate level,
in soil
Koua Bocca, Côte d'Ivoire
Depth: 1.1 m
Objective: x 2.5
PPL and XPL

**CENTRIFUGAL CORTIFICATION**

These well-rounded nodules contain a well-developed cortex around their nucleus. These nodules are embedded in a surrounding argillaceous S-matrix, with many grains of detrital quartz. These photomicrographs are meant to illustrate the regular peripheral fissures that are clearly seen around each nodule. These fissures, without appreciable sinuosity, exactly separate the nodule from its surrounding matrix. The nodules are of allochthonous origin, and have been transported, partially eroded or even broken, as shown by the discordant cortex in the nodule at B2, and by the isolated fragment of cortex at E2. Apparently, peripheral fissures are not developed around the smaller grains of detrital minerals.
S 13, S 14

CORRIFIED NODULES
in a soil developed at an intermediate level of a slope
Koua Bocca, Cote d'Ivoire
Depth: 1.1 m
Objective: ×2.5
PPL and XPL

WELL ASSEMBLED corrified nodules are embedded in the argillaceous S-matrix of a soil developed at an intermediate part of a slope. The outside of the nucleus and the irregularities of the cortex of the central nodule show that these nodules were formed higher on the slope before being transported and deposited at a lower level. All the nodules photographed, as observed under PPL, show a well-developed peripheral fissure, which isolates them from the surrounding matrix. Careful observation of the nodule-matrix contact shows that, in contrast to the nodules shown in both previous photomicrographs, the peripheral fissure is less regular. Furthermore, thin scales of the more external laminae of the cortex may become separated and isolated from the nodule by irregularities of the peripheral fissure. The granostriated birefringence-fabric, as observed under XPL, is only slightly developed around the nodules.
The section photographs show the "deformed" texture of a well-formed cortex as it can appear if it is cut, according to a polar section, by the plane of the thin section. The regular and constant thickness of the successive laminae of the cortex, such as they normally appear in an equatorial section, are apparently deformed in a more eccentric section: the more internal the observed lamina, the thicker it appears in the section. Theoretically, only an equatorial section will be able to show cortex laminae with their true thickness, and the nucleus should be visible in the central part of the section. The central circular portion of this concretion, as shown by this photograph, does not correspond to a section across its nucleus, but to a tangential section at the level of an internal lamina of the cortex. This may be proved by the homogeneity and absence of texture in that central part. The concentric distribution of the hematite-rich scales, which originate from the incorporation of plasma material, is clearly seen. The scales form thin crescents of dark-colored material alternating with yellowish brown goethite-rich material. The successively formed crescents are randomly distributed, and they appear in any angular position. The thick cortices are commonly fractured by very thin radial fissures, which cut them into irregular pyramidal volumes. The network of these thin fissures is clearly seen in most of the section. The lower photomicrograph shows the regular orientation of the goethite crystallites, as expressed by their birefringence and their extinction in a crossed pattern.
**Accretion Cortex Developed on Alterorelic**

Buried iron crust  
*Koua Bocca, Côte d'Ivoire*

Depth: 0.8 m  
Objective: × 2.5  
PPL

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**Accretion Cortex Developed on Alterorelic**

Buried iron crust  
*Koua Bocca, Côte d'Ivoire*

Depth: 1.2 m  
Objective: × 2.5  
PPL

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**B**ehind photomicrographs show alterorelics, exhibiting either a regular or an irregular shape, can be surrounded by successive laminae of the cortex, which are progressively more and more circular in section. The first photomicrograph shows a subsequent nucleus consisting of an ultrabasic alterorelic surrounded by the regularly concentric laminae of a thick accretion (centrifugal) cortex. Only the few first laminae closely follow the small external irregularities of the nucleus; additional laminae are more and more regular and circular (as seen in the plane of the thin section). The laminae of most of the external cortex are regularly concentric, and do not modify the general shape of the nodule. The second photomicrograph, in contrast, shows a triangular alterorelic. After the formation of the inner part of the cortex, the laminae become as rounded as is the cortex of the first example. Whatever the shape of the nucleus, the external shape of the composite nodule seems to be circular, or very nearly so, in the plane of the section.
A n all rocks that exhibit an oriented petrographic texture and fabric, as well as alterorelics that are developed from elongate lithorelics, have a tendency to be surrounded by a regularly elliptical cortex, as shown here. The ellipsoidal alterorelic, as in the first of the previous two photomicrographs, exhibits a good sphericity, but with a somewhat irregular and rough external border. The detail of the sinuosity of the border is followed by the first-formed laminae of the cortex but, quickly, these irregularities become subdued, and the laminae tend to be progressively less and less undulating and to show an increasingly smooth and elliptical shape outward. The alterorelic, derived from an ultrabasic rock, is composed of many crypto-alteromorphs after clinopyroxene (appearing brownish under PPL, reddish under XPL), and several meso-alteromorphs of kaolinite after biotite - vermiculite (pale in PPL, bright white under XPL), with some interstitial grains of residual magnetite. The accretion cortex is composed mainly of laminae of goethite, but the most external part of the cortex is abruptly composed of many laminae of hematite, the result of incorporation of scales of plasma within the cortex during its accretion phase. As in the other examples of iron crusts described in this chapter, the nodules are tangentially linked by bridges of indurated material, and relics of original plasma are isolated in the textural gaps maintained between the nodules.
521
ACCRETION CORTEX
OF GOETHITE
Iron crust
Koua Bocca, Côte d'Ivoire
Depth: 1.2 m
Objective: × 10
PPL

522
COMPOUND CORTEX
OF GOETHITE AND
HEMATITE
Iron crust
Koua Bocca, Côte d'Ivoire
Sampled at soil surface
Objective: × 10
PPL

The photomicrographs show the microlaminated texture of the accretion cortex formed around alterorelic nodules in an old indurated iron crust. The first one, at high magnification and under PPL, clearly shows the microlaminated texture of a goethite-rich cortex developed around a relict nucleus, partly visible in the upper left corner. In the lower right corner, thick laminae of hematite are due to the incorporation of shells of plasma near the matrix. The detailed view shows that the microlaminations, some micrometers in thickness, are regularly parallel, without any incorporation of grains of detrital mineral. The grey parts, which appear as slightly shaded areas in the right part and to the lower left, are due to the difference of orientation of the microlaminae, which makes the birefringence of the goethite more pronounced in those parts that are more closely parallel to the optic planes of the microscope. These areas should appear nearly at extinction under XPL.

The second photomicrograph shows the thin and undulating microlaminations of goethite that are irregularly interstratified between thick microlaminations of hematite, which originate from the incorporation of shells of plasma from the surrounding matrix.
This photomicrograph shows a grain of quartz that was trapped by and partially incorporated, simultaneously, into the cortex of two nearly tangential adjacent nodules. The existence of such a brittle bridge, which joins together two large nodules, also proves that these two nodules have not been displaced after the formation of their cortex, and that their cortex was formed in situ by the progressive replacement of the surrounding S-matrix.
This page shows a very thick cortex which, during its development, incorporated many grains of quartz originally included in the surrounding S-matrix. The quartz grains seem to be more numerous at certain levels of the growing cortex, and the more elongate grains seem to have been rotated in such a way that they are now preferentially oriented parallel to the general lamination of the cortex. This rotation is due to the directed pressures that develop in the contact areas between the hard resistant nodule and the soft compressible matrix. The quartz grains were incorporated in situ within the cortex, without any appreciable displacement; they were maintained where they were embedded in the S-matrix, whereas the front of cortification progressively invaded the matrix by an accretion process. The quartz grains are no longer chemically stable in this old iron-rich crust. Several of them have been completely dissolved, and have given rise to residual pores whose shape exactly corresponds to the shape of the dissolved grains. The late timing of the dissolution of the quartz grains, with respect to the time of cortex formation, is proved by the fact that no goethite laminae enter the residual pores or coat their internal walls. Some air bubbles were artificially trapped in some pores during the preparation of the thin section.
Two alterorelics of different origin are visible in this photomicrograph. The right-hand one is composed of a nucleus formed at the expense of an ultrabasic rock, whereas the one on the left formed at the expense of a granitic rock. Within the first one, the alteromorphic texture is still evident, with its opaque grains of magnetite and its phyllopo-ro-alteromorphs after olivine and clinopyroxene now replaced by iron oxyhydroxides. The original texture of this first alterorelic is not modified by the weathering process, which has replaced the secondary silicate minerals by iron oxyhydroxides. The second alterorelic is composed of many grains of quartz embedded in an iron-rich matrix in which the original texture is no longer identifiable. Both alterorelics are now completely surrounded by a micro-laminated cortex, but the cortex around the ultrabasic nucleus is much thicker than the cortex on the granitic nucleus. Both cortices are joined by a common bridge that probably formed more recently, after the deposition of the alterorelics. Indeed, it is highly probable that the first nucleus, originating from the upper part of the slope (developed on ultrabasic rock), was deposited with its own well-formed cortex, whereas the external part of the cortex, which formed more recently at a lower part of the slope (developed on granitic rocks) and which is common to both alterorelics, formed in situ after the meeting of the alterorelics in their colluvial deposit.
FURTHER EVOLUTION

Textural modification in transported nodules

Where surrounded by their double cortex (internal epigenetic cortex and external accretion cortex), these resistant nodules can be exhumed by erosion, transported along slopes, and deposited lower, in an environment whose physicochemical characteristics will determine their future behavior. The cortified nodules may become subjected to possible removal of iron, disaggregation, and progressive destruction of the cortices and of the residual nuclei. Note, however, that additional accretion of material may occur, to increase the thickness of the external cortex.

During their transport along the slopes, cortex-covered nodules may have been eroded, fractured or weathered: in this case, the new cortices developed on these fragments are discordant with respect to the accretion cortex of the first generation.

During transport, cortex-covered nodules may have been eroded, fractured or weathered; in this case, the new cortices developed on these fragments are discordant with respect to the accretion cortex of the first generation.

At the same time, different lithorelics, alterorelics and even pedorelics, derived from slopes of the watershed and with possible different ultimate origins, may become mixed and concentrated in the lower parts of the landscape. These can include cortex-covered quartz-free nodules derived from ultrabasic rocks, quartz-bearing nodules derived from granitic rocks, very finely textured and iron-rich nodules derived from schists, and nodules constituted of miscellaneous papules* covered by a later cortex. The occurrence of nodules of mixed origin, of fragmented nodules, of cortex-covered resistant organic residues, charcoal for example, and an abundance of skeleton* grains and of gravels of a similar size as the nodules, all may be encountered in the lower parts of the landscapes.

Interconnected and bridged nodules

The thickness of the cortices is related to the clay-mineral content (mainly the content of smectitic clay) of the surrounding internodular matrix. In the soils of the upper part of the toposequences*, where kaolinite predominates, or in the very porous or very sandy near-surface horizons, pressure constraints are minor around the nodules, and the cortices are relatively thin, or irregular, or even nonexistent. In the more compact lower horizons, with higher proportions of swelling clays, the constraint cutans and the derived cortices are ubiquitous and much thicker.

The thickness of these stress cutans* and cortices is also inversely proportional to the distance between two neighboring nodules. The oriented plasmas, which uniformly surround the nodules (granostriated b-fabric*), are extensively thickened in the areas where the nodules are close together. In this way, both cutans acquire ovoid shapes whose apices are ultimately joined together. A continuous envelope common to both nodules develops. The induration starts preferentially in these areas of high stress; as a result, both adjacent nodules may be surrounded, after development of a certain thickness of discrete individual cortex, by a single, common cortex, which is 8-shaped where observed in thin section. The stress is gradually higher, and the cortex thicker, as both nodules involved are closer one to the other.

In this way, two or more nodules can be joined together by indurated bridges. The local coexistence of several bridges can promote the complete isolation of volumes of internodular plasma.

Concretion and the formation of concretions

In addition to nodules of allochthonous origin, whose nucleus consists of a more-or-less replaced alterorelic, autochthonous nodules also can develop in situ. Their constituents are derived directly from the pedoplasma and as a result of its incorporation in the concretion. This process of concretion formation is very different from the process of cortification described above. Concretions do not result from the development of successive microlayers around a nucleus. Rather, they develop by irregular enlargement of a tiny concretion, whose volume increases by incor-
poration of volumes of pedoplasma and skeleton grains. The distribution of these skeleton grains within the concretionary nodule is similar to that observed in the pedoplasma. They are orthic concretions. Differences in extent of iron enrichment, which are expressed by differences in opacity, are common. Such concretions seem to be surrounded by a diffuse halo showing a decreasing content of iron oxyhydroxides (depletion halo). The concretions are more irregularly shaped than are the cortex-covered alterorelics described above, although they also have a tendency to be circular in cross-section. If the nodules are abundant, the true nature of the original matrix may be difficult to identify, since most of the matrix has been modified by loss and gain of iron oxide.

Where strongly indurated, these nodules may also be surrounded either by stress cutans showing a well-oriented texture and birefringent fabric, or by illuviation cutans. The concretion may also develop around a formerly developed nodule of any composition and origin. The newly formed concretion forms an external rim around the older nucleus or nodule. The distribution of the skeleton grains within the concretion's rim is similar to that of the internodular plasma, but it may be different from that of the central nucleus. These concretions of pedological origin are also possibly subjected to processes of degradation, involving the development of radially or concentrically arranged fissures and cracks. Loss of iron around the rim and along the inner network of fissures may occur at an advanced stage.

In environments rich in smectite-group minerals along the lower slopes, small, spherical, millimetric concretions of manganese oxides and hydroxides also may develop. These Mn-rich concretions may eventually be surrounded by a cortex showing accretion of ferruginous material. Within these lower profiles, they may be associated with variously sized and shaped nodules and concretions of calcite.
FURTHER EVOLUTION

Both photographs, taken of the same sample, show the beginning of the destruction of the nodule. The process begins by the formation and the opening of concentric curved internal fissures, which divide the nodule into successive shells and separate the nucleus from its external cortex. The cortex itself commonly becomes broken up into several relics by the opening of radially distributed fissures (upper photograph). Thin scales and shells of the cortex may also be progressively incorporated within the S-matrix by the irregular penetration of the peripheral fissures inside of the nodule (lower photograph). The separated parts are progressively assimilated in the matrix by dissolution of their iron content and by softening of their indurated material. Diffuse ferruginous halos may be encountered around such residues. The largest nodule in each photograph has already lost part of its cortex during a previous step of degradation, when displaced along the slope.
In contrast to the previous case, these two nodules underwent an important displacement after their cortex had formed. They were broken, and their surfaces were eroded before being again incorporated in a lower colluvial matrix. In the first photograph, the broken nodule is incorporated into the colluvial matrix of the middle part of the lower slope, where the geochemical conditions promoted the formation of a new cortex, which is now discordant with respect to the earlier cortex on the nodule. Residual pores after quartz are similar to the pores previously described.

In the second photograph, the second cortex, discordant on the first-formed one, also has been eroded during a further step of displacement to the lowest parts of the slopes. During the translocation of the nodule, both generations of cortex, as well as the included quartz grains, were eroded in such a way that the final shape of the complex nodule has become smooth and elliptical. The very sandy surrounding matrix does not allow a third cortex to form, and the nodule maintains the volume that it had at the time of its deposition.
BROKEN NODULES IN A LOWER COLLOUVIAL SOIL
Koua Bocca, Côte d'Ivoire
Depth: 1 m
Objective: x 2.5
PPL and XPL

Broken nodules were deposited in the colluvial material of the lower slope, on which recent soils developed. The surrounding matrix contains many unsorted detrital grains of quartz. A granostriated birefringence-fabric is clearly seen around the spherical nodules (D2), around the broken nodules (A–B2), and around the fragments of cortex (D1, C3). The presence of these broken nodules and fragments of cortex and, to a lesser extent, of the unsorted quartz grains, proves that the complete spherical nodules are also displaced allochthonous nodules, and thus not autochthonous pedological features, formed in situ. More careful observation on the cortex developed around the largest nodule shows some discordances between its internal microlaminae (D5), which also proves its allochthonous origin.
Further Evolution

Quartz-Bearing Lithorelic
Superficial soil
Koua Bocca, Côte d'Ivoire
Depth: 0.3 m
Objective: x 2.5
PPL and XPL

Phenomenally, the mineralogical matrix consists of quartz grains in which some grains exhibit the undulatory extinction characteristic of quartz grains originating from veins or from metamorphic intercalations. The external shape of the quartz part is very irregular, and exhibits large embayments, which are filled by a discontinuous cortex. This cortex probably formed, at least in part, at the expense of alteration morphs after feldspars, whose external shape appears as a very smooth and regularly rounded surface. During the previous displacement of this complex nodule, part of the cortex was eroded, which resulted in the slight protrusion of the hard quartz grains beyond the general rounded envelope of the nodule, and in the subsequent roundness of the protruding quartz grains. The pedological S-matrix is very porous. The part adjacent to the nodule exhibits the usually observed granostratified birefringence fabric. Detrital grains of hornblends, pyroxene and quartz are widespread in the surrounding S-matrix.
**SANDY COLLUVIUM**

Lowest part of the slope
Koua Bocca, Côte d'Ivoire
Depth: 0.7 m
Objective: × 1.6
PPL and XPL

**534, 535**

General view of a soil developed on sandy colluvial-alluvial material on the lowest part of the slope, in the vicinity of the Tare River. The coarse fraction of the area photographed contains an alterorelic after clinopyroxene (C3), recognizable by its porous, brown septo-alteromorphs after clinopyroxene, with a few opaque grains of magnetite, several more-or-less rounded cortilled nodules (E4), and several coarse grains of quartz (E1). The fine sandy material is mainly composed of irregular or rounded grains of quartz mixed with some detrital heavy minerals: clinopyroxene (A3, and to the right of the central alterorelic), hornblende (yellowish or brownish grains at D3 and B1) and a curved crystal of vermiculite (yellow elongate crystal to the lower right of the central alteromorph). All these coarse grains are uniformly surrounded by a thin cover of well-oriented argillaceous material. This particular feature of the soil material corresponds to a typical chitonic distribution (Stoops & Jongerius 1975).
Several alterorelics whose accretion cortex has become sufficiently thick to be linked by bridges. These are formed, firstly, by the junction at points of contact between two adjacent nodules, and later, by several junctions with more distant nodules while the first-formed bridges are progressively widened. On the short term, the curved gaps between the bridged nodules are occupied by the original S-matrix which, step by step, undergoes simultaneous induration by epigenetic processes and formation of residual pores by material loss. The second illustration shows, in somewhat more detail, the contact area between two adjacent cortices and the curved shape of the more external laminae of the common cortex (B3).
AUTHIGENIC CONCRETION
Lowest part of the slope
Koua Bocca, Côte d'Ivoire
Depth: 0.5 m
Objective: x 2.5
PPL and XPL

The pedological feature shown in these illustrations is an autchthonous orthic concretion formed by progressive concentration of iron oxyhydroxides in a part of a quartz-rich S-matrix deposited in the lowest parts of the landscape. In these colluvial sandy soils, subrounded autchthonous concretions are commonly associated with well-rounded allochthonous nodules (A2, A5), which originate from the upper parts of the slopes. The border of the concretion is irregular and sinuous, and the general shape is largely dependent on the abundance and size of the sand grains, which are only partially trapped in its external part. The smaller the quartz grains, the smoother the external envelope of the concretion. Once loosened from their matrix, such concretions exhibit a very rough shape owing to the great number of partially protruding quartz grains. The level of the induration is uneven, because ferruginous components are not equally distributed in all parts of the concretion. The upper left sector of the concretion photographed is much less indurated than its lower right part. A granostriated birefringence-fabric and hypocoatings are observed in the matrix that surrounds the concretion or along the peripheral fissures. The indurated parts of the concretion exhibit, under XPL, the birefringence usually observed in well-crystallized materials.

FURTHER EVOLUTION
The micrographs illustrate concentric rims of newly indurated orthic material around early-formed allochthonous orthic nodules. The nucleus, which is clearly distinguished in the central part of the mixed concretions, is, in the nodule on the left, composed of an irregularly cortified alterogenic containing large quartz grains. The nucleus of the nodule on the right is composed of a very opaque material containing few very small grains of quartz. These more-or-less well-rounded nuclei are surrounded by a corona of more recently indurated material in which the distribution of the quartz grains is obviously very similar to their distribution in the surrounding S-matrix. Many quartz grains, partially trapped by the concretions, protrude beyond the external limit of the iron-enriched areas. In contrast to the previous case (see 538 and 539), sharp boundaries are observed all around the two concretions.
542, 543

DESTRUCTION OF INDURATED FERRUGINOUS CONCRETION in old upper soils
Koua Bocca, Côte d'Ivoire
Depth: 0.2 m
Objective: x 4
PPL and XPL

Further evolution
illustrate a ferruginous concretion that formed in ancient soils, now eroded in the upper part of the landscape. The loosened concretion was recently embedded in the upper mantle of colluvium, which covers the soils and alterites formed at the expense of ultrabasic rocks, at a somewhat lower level of the toposequence. The limits of the concretion are irregular and polygonal. A peripheral fissure completely surrounds the main part of the concretion, whereas some relics of partially iron-depleted material (DE3, CS) are progressively incorporated into the surrounding matrix. Quartz grains now protruding beyond the concretion were probably entirely within the concretion when its volume was more extensive. Embryonic internal concentric and radial fissures run around the center of the concretion; they certainly will contribute to its further disaggregation.
This figure illustrates a spherical manganese-rich concretion, regularly surrounded by a thin ferruginous cortex. The optically opaque part of the nodule, which can be likened to a nucleus, exhibits the characteristic rounded shape of most manganese-rich concretions formed within the smectite-rich soils developed on basic and ultrabasic rocks, in the lower parts of the landscapes. Usually, basic and ultrabasic rocks have manganese contents higher than do sedimentary or granitic rocks. The alterites and derived soils may show relatively high contents of manganese oxides, commonly expressed as small spherical concretions. The concretions at a given level are all of equal size, and usually do not exceed a few millimeters, as in this illustration. These concretions are usually completely opaque, and they do not show any internal texture. In most cases, these concretions are surrounded by a smooth iron-rich cortex, whose orange color sharply contrasts with the black central part of the nodule. These nodules may be very abundant and regularly distributed at some levels of the toposequences, and they are commonly associated with or within nodules of micritic or sparitic calcite.
Bridged Nodules and the Development of Iron Crust

**Extension of the Bridged Textures**

The phenomena that promote the development of bridges between neighboring cortex-covered nodules can extend to most of the nodules of the horizon; by the extension of such an intertextic* texture, a true iron crust is progressively developed. All indurated alterorelics and pedorelics, surrounded by their own cortices, are linked together by indurated bridges that exhibit a more-or-less banded internal texture. Interconnected bridges and nodules divide the originally continuous pedoplasma or matrix into small isolated volumes.

Before the induration of the nodules is complete, the development of stress cutans is observed in the pedoplasma areas located between two closely spaced nodules. These cutans not only completely surround the periphery of the contiguous nodules, but they become thicker and enlarged, by increased pressure, within the narrow gap between them. These stress cutans are expressed, in optical microscopy with crossed polarizers, as strongly birefringent areas. These areas are the most suitable for further induration. As a result, indurated bridges will form to weld the closest relics. More and more relics are progressively linked together owing to indurated bridges. In this way, volumes of plasma are ultimately isolated each from other. Their further evolution can thus be arrested or delayed. The cortification that develops at their expense locally is arrested, and can proceed only within the volumes of matrix that are still interconnected, in which the quantities of argillaceous pedoplasmas and illuviations are sufficient to promote pressure constraints.

**Micromorphology**

In a detailed study at a scale available by optical microscopy, the cortification of bridges seems to be still more complex. At the contact between two small-sized nodules, the common cortex exhibits, in the area of the joining bridge, a sufficiently reduced width to allow its complete, regular and uniform induration. The bridge is indurated throughout all its thickness. In contrast, at the contact between two coarse-sized nodules, the bridge that contains the compressed plasma is rather longer and larger. Consequently, its induration can proceed only at the rims of the bridge, which isolates in its central area small volumes of interstitial plasma. These volumes are completely isolated, and they normally cannot evolve further. Reconstructed in three dimensions, these large bridges appear as hyperboloid volumes, or as double cones opposed at their apices, with indurated peripheral rims, but whose central part maintains an unindurated volume of plasma. These volumes of plasma belong to the first generation, i.e., that plasma which, until this stage, surrounds the entire nodule.

With aging, most volumes of plasma that are isolated within the bridges will become enriched in hematite, will be indurated and will strengthen the previously formed and partly consolidated bridge. Under some circumstances, in contrast, these volumes of plasma will disappear and will be replaced by pores. The intertextic bridge is then reduced, if observed in thin section, to a kind of a "double tombolo**". Within the external parts of these bridges, the internodular areas of plasma, until now interconnected, continue their evolution, on one hand, by progressive thickening of the bridges and cortices that surround them and, on the other, by dissolution and slow clearing of the constituent clay minerals. A relative concentration of the skeleton grains, which were originally included in these volumes of plasma, is progressively developed.

These gradually indurated horizons may be shallowly buried, near the soil surface; as long as most areas of plasma remain soft and interconnected, root sections, charcoal fragments and coprolites may be observed within them. Where subjected to processes of superficial weathering, these volumes of plasma may become excavated and completely emptied. A low-density iron-rich crust is then formed in which interconnected, alveolar, amoeboid empty pores are observed. Under conditions of normal burial, how-
ever, these volumes of plasma are not removed. With aging, these residual volumes of plasma of the first generation are replaced by skeletal, sandy and porous materials that form a second generation of pedoplasma. This latter pedoplasma exhibits a composition and a texture very different from those in pedoplasma of the first generation, such as it can still be observed in the central part of the bridges.

Around these evolving areas of pedoplasma, the process of cortification continues. The nodular concentric cortices and the banded cortices of the intertextic bridges are gradually thickened. The volumes of the internodular plasma progressively decrease until they become ultimately isolated and disconnected by the thickening of the banded cortices and by the obstruction of the connections; they stop their evolution, and become fossilized at various stages of their degradation. The last elementary microlayers of the banded cortices form by accretion upon the previous ones. They are thus microlayers of centrifugal cortification (with respect to the nodules), although the progressive decrease of the central volume of plasma, at the expense of which the thickening of the cortex takes place, rather suggests a centripetal process of cortification (with respect to the volume of plasma).

The volumes of plasma may also be indurated without any observable cortification. They then become distinguishable from indurated alterorelics, from which they are separated by regularly concentric or distorted banded cortices, only by their different colors, hardness, porosity or microtexture.

A first generation of iron crust is formed which, later, will evolve, according to its own rules under the repeated and alternating conditions of dissolution, of internal displacements and transfers of material, and of recrystallization, to produce indurated iron crusts such as they are observed today.

**DISTRIBUTION OF THE INDURATED AND UNINDURATED PLASMAS**

Ultimately, the protonodular iron crust, at the end of its evolution, contains four mineralologically and texturally distinct parts.

**The nuclei**

The nuclei of all nodules are indurated alterorelics of miscellaneous original rocks, especially in the case of a lower-slope deposit, whose internal fabric is generally obscured or destroyed. Most relics have been displaced before their weathering and before their induration. They are commonly goethite-, hematite- or, in some instances, manganese-rich nodules. They may contain grains of quartz and other residual minerals if their origin allows it. These nuclei also contain the internal part of the cortex, which results from partial, peripheral and centripetal epigenetic replacement. In many cases, this internal cortex is composed only of goethite, in which the same residual minerals as those observed in the nucleus can perhaps be included.

**The concentric and interconnected cortices**

The concentric cortices that surround the alterorelics and the banded cortices that join them do not exhibit any significant differences of composition or microtexture. Both have evolved directly from the internodular pedoplasmas. The concentric cortices commonly consist of goethite without hematite, whereas the banded cortices commonly consist of discontinuous layers of hematite alternating with continuous layers of goethite. The residual minerals that may occur within these cortices are essentially those that are observed in the internodular plasma. After their incorporation within the accretion cortex, minerals such as quartz, in geochemical disequilibrium with their iron-rich environment, may be completely dissolved, yielding empty pores.

**The large volumes of plasma**

The large volumes of plasma, in many cases, rich in skeleton grains of quartz, correspond to more-or-less isolated relics of the pedoplasmas, in which the alterorelics were embedded before their cortification began. The composition of the internodular plasmas is highly variable. It depends on the petrographic and mineralogical nature of the parent rocks, on the pedological processes, and on miscellaneous processes of near-surface origin. They may be argillaceous or rich in skeleton grains; the clay minerals may consist of kaolinite or a member of the smectite group; their content of iron and of organic matter strongly depends on their location at the profile and landscape scales. These plasmas may lose their clay-mineral content, either by
dissolution or by mechanical transfer. Very porous volumes are the only result, and residual skeleton grains are freely distributed in them.

The small volumes of plasma

The small volumes of plasma, of the same origin as the larger volumes but isolated in the bridges and cut off from any external transfer, are not involved in the general evolution of the progressively indurated horizon. At the beginning, their composition is similar to that of the surrounding pedoplasma. Subsequently, within the cortified bridges, their composition evolves very slowly, either by alveolization and by formation of practically closed empty pores, or by addition of iron and enrichment in hematite. Both types of plasmas, the first one fossilized within the bridges, the second more or less evolved within the large internodular volumes, can be observed together in the same sample at the scale of a thin section.

DISCUSSION

The various textures of the plasmas commonly observed in the most widespread iron crusts do not necessarily result from successive steps of replacement of the groundmass by various generations of plasmas (due to pedoturbation, epigenetic replacements, dissolution, displacements of material, internal erosion and infilling). These processes, although often invoked, do not account for the variations in color, induration, porosity, microtextures, geochemical content and mineral assemblages of the different parts of the iron crusts, as observed in thin sections. Instead, the apparent successive steps of formation or replacement of the plasmas may simply be due to differential evolution of the original plasma. Domains of plasma may still be interconnected (and thus subject to further evolution), or they may be isolated by surrounding cortices and bridges, in which case they are temporarily fossilized, without further evolution.

The observation of a given area of iron crust in thin section corresponds only to the "instantaneous" observation of a domain of a complex material whose various parts are each evolving at very different rates.

The intermediate steps of evolution are only rarely observable in a single thin section, as it is representative of a very small volume of the material. The chronology of these intermediate steps can be deduced only by careful and critical observation of large-sized thin sections, prepared from a series of samples regularly and closely spaced in the profile. Such observations, at a microscale, usually cannot be performed by direct observations in the field. Patterns of spatial distribution and genetic relationships cannot be easily deduced from observations of the profile at the macroscale. Furthermore, the character of a given area, either interconnected or isolated, is not obviously detectable in thin sections, even in the largest-sized sections, because the interconnections or the separations are very complicated, intricate and, in most cases, perceptible only in the third dimension.
EVOLUTION OF THE RESIDUAL VOLUMES OF PLASMA IN INDURATED IRON CRUSTS
Koua Bocca, Côte d'Ivoire
Depth: 1.2 m
Objective: x 1.6
PPL

The lower portion of a photomicrograph shows a fragment of iron crust transported and now buried in colluvial material. The fragment of crust is slightly indurated, and its cohesion is due only to the numerous indurated bridges to the adjacent cortified nodules. These are spherical, and they exhibit a cortex whose thickness is related to the period of time during which the lithorelics were embedded within a matrix favorable to their cortification. That cortification has continued at the expense of the S-matrix, and the last-formed laminae have bridged, one after the other, nearly all the nodules observed here; the first-formed bridges (A1–2) are slightly wider than are the more recent bridges (C1, C4), and several nodules do not seem bonded together (E4). In this last case, the contact may be beyond the plane of the thin section, but the neighboring volumes of interstitial plasma are still interconnected. The residual interstitial volumes of plasma are widely interconnected during the first steps of the cortification. Gradually, as the cortices grow, the residual volumes of plasma become smaller and smaller, and ultimately more and more isolated. As long as they are connected and as long as free circulation of water allows the cortex to grow at the expense of the plasma, its evolution is supported, and the volume of plasma progressively and proportionally decreases. The quantities of water percolating among the nodules become proportionally more and more important, and many volumes of plasma lose their clay content and leave a very porous residue composed of sand particles. As soon as these residual volumes are completely isolated, their evolution follows a different path, which consists of their slow replacement by hematite. The very small residual volumes, which appear in the central area of the bridges, are quickly and completely isolated from the general evolution of the residual S-matrix. As soon as they are isolated, they are replaced by hematite without passing through a step of leaching. This photomicrograph exhibits many residual volumes of S-matrix, most of which are probably interconnected in the third dimension. Most exhibit the initial aspect of the untransformed matrix.
This photograph shows wide bridges interconnecting at least four nodules (A1, B3, E1 and E4). The largest nodule, on the left, appears (in the plane of the thin section) as a polar section of a still wider nodule; only the external hematite- and goethite-rich laminae of its cortex are visible, whereas its nucleus lies beyond the thin section. The largest one on the right is an equatorial section of a nodule, in which both nucleus and cortex are distinctly visible. The external part of the main bridge, which binds together the nodules at B3 and E4, consists of a continuous thick lamina of goethite-rich material, which is in textural continuity with the external part of both adjacent cortices. This lamina alternately follows nodules and bridges, and it probably is continuous over long distances. The inner part of the main bridge consists of a volume of interstitial S-matrix, which was quickly trapped, and which was later replaced by hematite. Traces of the former granostriated birefringence-fabric are still distinguishable where hematite-rich and goethite-rich bands alternate. Scales of red plasma were also irregularly incorporated into the nodule during the formation of its yellow cortex. Unmodified residual volumes of interstitial S-matrix are visible as dark and porous amoeboid islands, at C2 and C5.
This page shows a complex bridge that binds two main nodules (B1 and ABCDE5) to a third one (D2), which is just visible as a polar section in its external cortex. The large triangular bridge shows the different steps in the incorporation and induration of the interstitial matrix. At B3, scales of red plasma matrix are incorporated within the goethite-rich laminae of the cortex. At C2, indurated yellowish and reddish plasma contains some quartz grains. At D3, in an incipiently replaced, reddish brown volume, the original textural fabric is maintained. At B1 and E2, volumes of S-matrix plasma are maintained beyond the nodules and the bridges. The partial leaching of their clay content promotes the formation of sandy and very porous residues.
Evolution of the residual volumes of plasma in indurated iron crusts
Koua Bocca, Côte d'Ivoire
Sampled at soil surface

Objective: x 1.6
PPL

This photomicrograph, and the next one, show the macromorphology of a very porous iron crust formed at the expense of an S-matrix that originally contained many small allochthonous alterorelics. Parts of the concentric laminae of the cortex that developed around the alterorelics may have formed before deposition of the nodules in the S-matrix. The small size of the nodules allows the photographs to show proportionally wider parts of the iron crust, to understand the chronology of its formation, and to better visualize the successive inheritances and the evolutionary steps of its components. At the beginning, the S-matrix occupied all the available volume among the alterorelics. The location of the geometric center of all these alterorelics has probably not been modified during all the further steps in the transformation. It is an isovolumetric transformation within an undisturbed material.

The photomicrograph clearly shows the chronology of the evolution of the indurated iron crust. In the first step, all the alterorelics are progressively surrounded by a further cortex, which develops either at the expense of the volume of the surrounding matrix or by concentric juxtaposition of thin laminae formed by crystallization of goethite in the peripheral fissures. In the second step, as the size of the nodules gradually increases, some of them become sufficiently close to each other to allow bridges to form. Small volumes of S-matrix that are trapped within the bridges (B4, E2) are slowly indurated by replacement by hematite. In the third step, the first-formed bridges are progressively widened, and some of them may link several nodules (C3). Concomitantly, the total volume of the residual S-matrix progressively decreases. In the fourth step, as soon as large bridges that join many adjacent nodules are formed, the residues of plasma, which up to this point were interconnected, suddenly are isolated (D3), and their further evolution is suppressed. The volumes that are still interconnected are subjected to a leaching process, by proportional increase in the volume of percolating water, and they lose most of their clay content (CDE1, D5).
This microphotograph of the same sample of iron crust as in photomicrograph 548 shows better the very porous sandy residues after the S-matrix has lost its clay components. It seems obvious that these volumes really originate from the original S-matrix, and not from the infilling of allochthonous material into previously formed empty connected pores. In this latter case, indeed, the infillings certainly would exhibit a concentric or a crescentic texture, similar to that usually observed in clay deposits, either in open pores and fissures or in biopedotubules.
The photographs show the evolution of remnants of the S-matrix where nodules and matrix exhibit an open porphyric* distribution. The matrix can evolve over long periods of time before being divided into isolated volumes by the growth of cortices and bridges, formed around the included nodules. A cortex first develops around each nodule, and grows until the distance between adjacent nodules becomes sufficiently small to promote the formation of a bridge. A common and continuous cortex is then formed around the bridged nodules. Such a cortex is formed at the expense of remnants of the matrix. Each contorted or sinuous cortex progressively becomes more and more circular in shape as the thickness of the cortex gradually increases, and as the volume of residual matrix decreases. The matrix is progressively replaced in a centripetal process of cortification. All the concentric microlaminae result from a progressive cortification of the surrounding nodules which, previously isolated from each other, now form a complex macronodule. From a genetic point of view, all cortices arise by true centrifugal accretion around nodules, and not by centripetal replacement. The pattern of evolution of the remnants of matrix, once completely isolated, is developed as previously described.
INTRODUCTION

Beneath lateritic plateaus, whose bauxitic cover exhibits isalteritic or alloteritic textures, a different type of bauxitic crust is commonly observed. It exhibits a very characteristic pisolitic texture, and a practically constant habit. This kind of bauxitic material is mainly characterized by the abundance of pisoliths, which are spherical nodules, typically four to eight millimeters in diameter, composed of an untextured and homogeneous nucleus uniformly surrounded by a more-or-less regular cortex. The interstitial volume between the pisoliths consists of a very fine-sized, indurated and generally featureless matrix. The pisolitic bauxites, where they have not undergone further degradation, are compact, and vary from red to reddish brown, the nuclei of the pisoliths generally showing a slightly darker color than the interstitial matrix. In a given sample of indurated bauxitic crust, most of the pisoliths are equally sized, exhibit a cortex of constant thickness, and are homogeneously distributed.

Most examples of pisolitic bauxite are strongly indurated. Their mineralogical composition is relatively uniform; they consist of an intimate mixture of bohmite and hematite. Gibbsite and goethite are rarely encountered in undegraded pisolitic bauxites, and residual minerals (kaolinite and quartz) are practically never encountered. Pisoliths can be so abundant that where observed on a cut sample of rock or in thin sections, the bauxite seems to be composed of closely spaced, practically joined pisoliths separated from each other by a minor amount of interstitial matrix. Nevertheless, even in the case of very closely spaced pisoliths, polygonal sections of pisoliths and common cortices joining neighboring pisoliths are never observed. These textures and compositions are typical facies of the pisolitic bauxites.

PROCESSES OF FORMATION

Detailed field and laboratory studies have produced pertinent data about the mechanisms involved in the formation of pisolitic bauxite (Boulangé 1970, 1984, Bocquier et al. 1983). These mechanisms of formation are determined by the reciprocal and overlapping influences of micromorphological, mineralogical and geochemical processes. In subsequent discussions, the geochemical processes responsible will be only alluded to briefly, and the description of the mechanisms involved will be reduced to the minimum necessary for an easy understanding of the micromorphology of both undisturbed or degraded pisolitic bauxites and of their lateral distribution in the landscapes.

Residual lateritic bauxite, which caps the highest plateaus, is characterized by relatively uniform and macroporous crystalliplasmas of gibbsite and hematite, in some cases associated with minor amounts of goethite. In the opinion of the above-mentioned authors, the formation of pisolitic bauxite results from the late in situ transformation of isalteritic or allalteritic ferruginous bauxite by geochemical processes, variable in terms of time and space, and which are responsible for alternations of increase and decrease of the iron content of the residual bauxite.

In a first step, relict nodules of lateritic bauxite are formed by the progressive replacement of the macroporous gibbsite-rich crystalliplasma* by an internodular bohmitic- and hematite-bearing plasma whose microporosity has favored the destabilization of the gibbsite and its replacement by the relatively less hydrated bohmitic. In this way, residual nodules are formed from a residual aluminous and ferruginous bauxitic crust, by centripetal concentration of iron. These relict nodules thus become completely surrounded by a bohmitic-bearing and iron-rich internodular plasma. Note that this progressive transformation is performed in situ without any crumbling or decrease in the hardness and compactness of the bauxitic crust. All parts of the relict nodules may finally disappear in favor of the internodular plasma, which progressively extends throughout the entire volume of the original bauxite.

During a second step, which can be synchronous with the first one, new nodules of plasma are formed by
internal differentiation within this böhmite- and hematite-rich internodular plasma. These nodules are roundish and exhibit the habit and size of the nuclei of the later-formed pisoliths. They are slightly more iron-rich than the internodular plasma.

During a third step, a new process of nodule formation leads to the redistribution of the iron and to an inter nodular differentiation by centrifugal concentration of iron. If the central part of the nodule is completely iron-depleted, the böhmite itself can be destabilized and replaced by new crystalliplasmas of gibbsite. Internally zoned nodules are formed, around which a perinodular void is progressively developed. This void may be responsible for later destabilization of the inter nodular plasma and later transformation of its böhmite content into new generations of gibbsite. Iron-rich perinodular cortices are progressively formed around the nuclei of the nodules of plasma, and true characteristic pisoliths are finally formed.

**Formation of pisoliths in bauxite**

(After Boulange 1984)

Pisolitic bauxite may form at the expense of either isalteritic or alloteritic bauxite. In either case, the transformation involves the degradation of bauxite in a fluctuating geochemical environment, in which iron is in some instances added, whereas in others, it is lost. The transformation influences, at the same time, geochemical, mineralogical and structural aspects of the assemblage. In parallel, there are adjustments concerning the nature of the hydroxide of aluminum. A transformation of gibbsite to böhmite accompanies the net addition of iron, whereas the converse transformation accompanies the net loss of iron. Inasmuch as migration of iron and modifications of minerals are important, the formation of pisolitic bauxite also has a structural dimension. Nodules and concretions are degraded in a centripetal fashion in an environment of iron loss, whereas nodules form and accretion on the cortex occurs, with centrifugal migration of iron, in an environment in which iron is added. The formation of pisolitic bauxite, therefore, is the result of a degradation, accompanied by the formation and evolution of glaebules*, at the expense of either isalteritic or alloteritic bauxite.

**Distribution in the landscape**

The mode of formation of the certificated pisoliths shows some analogies with the themes developed in previous chapters concerning the formation of the certificated nodules and their evolution in the podoplasm. In light of the discussion that came before, explanations can now be given about the formation of pisolitic bauxite.

The chronological development of the successive steps involved in the formation of pisoliths and pisolitic bauxites, and of their specific distribution in the landscapes, is given below to allow the reader to get a better understanding of the geomorphological and micromorphological processes involved, both at the scale of the landscape and of the thin section.

Geomorphological and sedimentary processes are described here as being the dominant controls on the chronology of the events involved in the formation of pisolitic bauxite, even though geochemical processes also are responsible for details of the formation and development of the observed microtextures.

This short section will be written with fewer details than the former ones. Geomorphological observations seem sufficient to provide the general basis of the origin of these pisolitic bauxites.

**Remark**: The proposed explanations result from careful observations of thin sections of the author’s own collection, and of many additional thin sections of pisolitic bauxites from Côte d’Ivoire, kindly placed at his disposal by B. Boulange.

**Erosion of the bauxitic profiles**

Beneath the lateritic bauxitic crusts that cover the tops of the plateaus, developed in some cases over a thickness of ten to fifteen meters or more, a very thick and poorly indurated alloteritic or isalteritic weathered mantle is generally observed. It developed by the weathering of schists and various metabasic rocks that constitute the volcano-sedimentary basement of most bauxitic plateaus of the Côte d’Ivoire. Diabase also was observed, for example, in the complex basement of the Orumbo Bocca (Boulange 1984). Subjected since the early Tertiary to strong weathering and processes of erosion, such areas of bauxite have been progressively reduced to the state of residual plateaus. On their slopes, and under a more recent cover of colluvium, truncated isalteritic horizons are observed, whereas near the top of the slopes, the very thick bauxitic crust
forms a subvertical and subcontinuous cliff, some ten meters high.

**Deposition of clayey material on the slopes**

Processes of erosion are responsible for the removal of enormous volumes of subjacent loose allo-tertic and isaliteric materials, originally protected by the indurated bauxitic cover. These materials were spread out on the slopes of the residual plateaus. Several successive pedogenetic processes have acted upon these materials. The resulting kaolinite-rich colluvium has the dark red coloration characteristic of soils and near-surface materials developed under humid tropical conditions.

Similar processes of progressive and continuous erosion have led to similar results over very long periods of time. Red materials, more recently cleared off from the level just below the indurated bauxite (and thus not indurated), are now visible in proximity to some cliff of bauxite near the summit. These reworked materials are actively used either as pottery material for their high clay content, or as support for cacao plantations owing to their fertility and favorable texture. These red kaolinite-rich materials are generally very homogeneous and well sorted. They only contain very small red papules* and small bauxitic or ferruginous relics. The sand fraction of this material, derived from the weathering of schistose volcano-sedimentary rocks, is very minor or nonexistent. Some horizons, at a depth of one to two meters, although not indurated, are not used for pottery because they contain abundant pisolitic nodules.

These spherical nodules have formed in variable quantities depending upon the local conditions of drainage, the composition or texture of the colluvial material, and the depth of the non-eroded subjacent autochthonous material. It is likely that similar clayey deposits, with similar pisolitic nodules, have formed during the Tertiary along all the slopes around the pro­

...
some of which have a biological origin. (b) Rare gibbsite-rich pedorelics appear with opaque plasma in PPL, which appears dark red in XPL (with condenser lens). Some opaque grains (magnetite) are observed. (c) Ferruginous concentrations occur, locally with diffuse margins in the vicinity of voids (quasiferrants). Hydromorphic characters are weakly and locally developed.

**Evolution of the clayey material**

Both pisoliths and matrix in these old, soft, nodule-containing, near-surface materials can later be completely indurated (to give pisolithic bauxite of the first generation); in contrast, they may have been newly eroded, transported downward and deposited on the lower parts of the slopes. After having been indurated, they form pisolithic bauxite of a second generation. During this later process of erosion, pisolithic nodules are "cleaned" and separated from their soft matrix, they are transported, eroded, they may be broken into pieces, and mixed together with other pedorelics or other fragments of bauxite. Many pisoliths, when denuded and exposed to surficial processes, are cut by radially or concentrically arranged fissures that facilitate their later fragmentation. All have lost their surrounding soft matrix. The material that is deposited down-slope may be enriched or depleted in pisoliths relative to the original material. The pisolithic bauxites of the second generation seem to be much more widespread in the landscapes than the pisolithic materials of the first generation, whose occurrence is restricted to small areas irregularly distributed around the bauxitic cliffs of the summit plateaus.

**Process of induration and development of pisolithic bauxite**

The further induration of the internodular matrix, in the pisolithic material of either first or second generation, gives way to pisolithic bauxite by weathering of the kaolinitic content of the material and its replacement by böhmite, in these finely porous and practically anhydrous media. The iron hydroxides are converted to hematite. The indurated pisolithic bauxite of the first generation and that of the second generation are not identical. Whereas all the pisoliths are of equal size, closely spaced and uniformly distributed in bauxite of the first generation, the pisoliths observed in bauxite of the second generation are heterometric, and most of them exhibit broken cortices and even broken nuclei. These fragments are surrounded by a new aggregation cortex, which is now discordant on the relics of the cortices of first generation that were spared during the transport of the individual pisolith. The pisoliths may also be mixed with indurated relics of different materials. In some cases, large rounded fragments of pisolithic bauxite of the first generation have been observed within pisolithic bauxite of the second generation. In pisolithic bauxite of the first generation, the pisoliths may be more numerous, as they are closely spaced or even touching each other, whereas their distribution is generally more dispersed and irregular in pisolithic bauxite of the second generation. Regularly shaped pisoliths newly formed in situ may develop within the secondary material before its later induration. These are mixed with previously formed pisoliths and pedorelics. Two similar families of pisoliths thus can be encountered in bauxite of the second generation.

Regardless of their nature, the pisoliths of the first generation, once they are embedded in bauxite of the second generation, never exhibit traces or relics of the original interstitial matrix attached to their cortex. This observation shows that at the time of their erosion from the first-pisolith-bearing horizon, the interstitial matrix was soft and unindurated. This property allowed the cleaning of the external surfaces of the transported pisoliths. It is only much later that the pisolithic horizons of the first generation (those not removed by erosion), and those of the second generation (which were formed at the expense of the first-generation pisoliths), become well indurated by replacement of the kaolinite content of the interstitial matrix by a böhmite-rich material associated with uniformly distributed hematite. This hematite gives the bauxite its characteristic red coloration.

**Profile of the pisolithic bauxite**

All occurrences of pisolithic bauxite, which are essentially developed from colluvial materials, are now observed as discordant bodies resting upon subjacent alitrites and rocks. A gap generally exists between these lower in situ materials and the allochthonous pisolithic bauxite at the top of the profile. Transitional horizons between the saprolite and the pisolithic bauxite are never observed. The gap corresponds to a phase of erosion that has notched the basement headward and that preceded the deposition of materials derived upstream.

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Most of these occurrences of pisolitic bauxite are now dismantled. Blocks and boulders of more or less degraded pisolitic bauxite are scattered on the upper parts of the slopes developed around the remaining plateaus of lateritic bauxite. The pisolitic bauxite, which is also a very old near-surface formation, has been actively eroded since the Tertiary. New erosional glacis have been formed beneath and downslope of the pisolitic horizons, whose relics are now scattered either on the slopes or the top of the surrounding residual small hills that the pisolitic bauxite has protected from erosion on the short term. A gap always exists between residual lateritic bauxite and pisolitic bauxite, either laterally in the landscape or vertically in the profile. The author has never observed transitional bauxite whose texture, composition and mineralogy could be directly understood without the external and successive interventions of geomorphological processes.

**Micromorphology**

The microtextures of undegraded pisolitic bauxite, of either the first or the second generation, are relatively simple and constant. The hematite content of the pisoliths and of the interstitial matrix is commonly so high, about 20% Fe₂O₃ for the whole bauxite (Boulangé 1984), that the bauxite appears practically opaque in thin section. It is necessary to greatly reduce their thickness to enable the observation of the textural details of both pisoliths and internodular matrix.

In contrast, these textures are clearly observed in iron-depleted bauxite (see below), in which the Fe₂O₃ content decreases to about 4%. The Al₂O₃ contents are 50 and 65% in original and iron-depleted bauxites, respectively. The total SiO₂ contents, which are related to the amounts of primary and secondary minerals that have survived the formation of böhmite and the degradation of gibbsite, are less than 4 and 1%, respectively (Boulangé 1984).

Micromorphological observations indicate that the pisolith normally consists of an untextured spherical nucleus surrounded by a continuous, regular, microlaminated cortex.

**The nucleus**

The nucleus is generally opaque and apparently homogeneous at the scale of observation available in optical microscopy. It is strongly indurated, and its hematite content is high. Most nuclei are compact and unfissured. Nevertheless, in the case of pisolitic bauxite of the second generation, many nuclei are cut by an irregular network of radial fissures, in some cases combined with incomplete concentric fissures, in which thin crystalliplasms of gibbsite may be observed. The minerals present, as determined by X-ray-diffraction analyses, are böhmite and hematite. No residual minerals or alteromorphic textures are observed.

Thin sections of pisolitic bauxite are commonly incompletely impregnated by synthetic products because (a) the nuclei are protected by the practically impermeable cortex, and (b) the interstitial volumes of matrix are protected by the numerous closely spaced pisoliths. A second impregnation is always necessary before grinding the surface of the slices.

**The cortex**

The cortex that surrounds the nucleus is regular, and very finely laminated. All pisoliths of a given bed of pisolitic bauxite of the first generation generally exhibit a cortex of comparable thickness, whereas the pisoliths of bauxite of the second generation can exhibit a compound cortex of variable thickness. The cortex also is composed of böhmite and hematite, but with a small proportion of goethite, which gives the cortex a more brownish or yellowish brown hue than either the nucleus or the matrix. Gibbsite is only observed as an infilling of radially or concentrically arranged fissures, which develop by degradation of the originally compact pisoliths. In contrast to the cortices developed around the nodules described in a previous chapter, the cortices of pisoliths do not contain any distinguishable feature originating from the internodular matrices. The cortices that surround a radially fissured nucleus are not necessarily fissured themselves unless they are surrounded by a more recent cortex of the second generation. In this case, the fissuring is concordant and continuous through the nucleus and the residual internal cortex. Fissures seem to have developed before the formation of the aggradation cortex of the second generation.

**The internodular matrix**

The internodular matrix commonly exhibits a microtexture very similar (color and degree of induration excepted) to that of the nuclei of pisoliths. It is homogeneous colored in shades of reddish brown; it has a low porosity, and is not fissured. It does not contain other features than pisoliths. Only the matrix of pisolitic bauxite of the second generation possibly...
contains some different features, such as relics of iron-rich or bauxitic crusts and ferruginous or gibbsite-bearing phanomorphic residues. There is no trace of a granostriated b-fabric. The matrix also is böhmite-rich, but the hematite content is generally lower than in the nucleus.

The detail of the microtextures of both pisoliths and internodular matrix can only be clearly observed, by optical microscopy and with thin sections of usual thickness, in the samples that have begun degrading by selective leaching of their opaque components (i.e., iron-bearing minerals such as goethite and hematite). The colorless and transparent böhmite-rich fabric allows the details of the microtextures, fissures, infillings and microlaminated textures to be clearly observed. All these textures are not affected or modified during the general bleaching of the bauxite, at least during the first steps of its evolution.
Red argillaceous material sampled near the hill top Dieula Bocca, Côte d'Ivoire
Depth: 1.2 m
Objective: ×10
PPL and XPL

This material was sampled near the summit of the plateau, downstream from the autochthonous bauxite at the summit, and upstream with respect to the first observed outcrops of allochthonous pisolithic bauxite, which occurs on the slopes. Its topographic location, grain size, mineralogical composition and color are such that this material can be reasonably considered, before its later induration, as the parent material of the pisolithic bauxite of the first generation. The thin section is shown to demonstrate the similarity of this material with the material of the next illustration of pisolithic bauxite. In the lower part of this profile, at a depth near 1.5 m, a nodular horizon appears in which many autochthonous rounded pisoliths are developed. At the beginning of their formation, these pisoliths do not contain a cortex, and they exhibit only the inner part (nucleus) of the later-formed pisoliths. Once better developed, they get a progressively thicker microlaminated cortex. Samples of that nodular horizon were taken, but unfortunately, owing to their lack of consistency, they crumbled during their transport, and no thin section could be made. More detailed explanations of this argillaceous material are given in the main text.
PISOLITHS IN BAXITE

TWO PISOLITHS (Figures 554A and 554B), and the next one, show a typical pisolith, of the type commonly encountered in the bauxitic crusts that cover the lower part of the slopes around isalite or alloberite bauxite near the summit. In the same way as a cortex may develop around hard indurated nodules in horizons of loose clay-rich soil (see the previous photographs), a cortex may also develop around nuclei in the ferrallitic and soft red material, at the expense of which pisolitic bauxite is formed. A typical pisolith is composed of a round nucleus that is regularly surrounded by a microlaminated cortex. The pisoliths are included in a continuous and homogeneous matrix. In undisturbed pisolitic bauxite, all components, nuclei, cortices and matrix are densely colored by hematite impregnations, and very thin sections must be prepared to make them sufficiently transparent for optical examination. The aluminous support is generally boehmite. The diameter of the pisoliths usually observed is around 5 mm, but larger ones may occur.

The inner nucleus, whose internal fabric is generally obscured by the opacity of the dark red material that composes it, is generally divided into polygonal volumes by a radial network of interconnected open fissures. The density of this network is commonly greater in the peripheral area of the nucleus than in its central area. In undisturbed pisoliths, concentric fissures generally are not developed. The radial fissures may have become infilled by microcrystalline gibbsite. The cortex is generally thick, and its thickness is generally slightly less than the radius of the nucleus. The cortex is not fractured, either by radial or by concentric fissures. It is microlaminated and generally homogeneously textured all across its thickness. Double or triple cortices of slightly different color are observed in some instances, as in the present case. In the typical pisolitic bauxite, the nonporous interstitial matrix is homogeneous, does not contain grains of detrital minerals, and is not separated from the pisoliths by a peripheral fissure. The matrix also is indurated, as are the pisoliths. All these general descriptions may have a number of local exceptions.
PISOLITHS IN BAUXITE

PISOLITIC BAXITE
Lower slopes of the Diedka Bocca, Toumodi, Côte d'Ivoire
Sampled at soil surface
Objective: × 1.6
PPL

The photomicrograph shows the first steps of the slow degradation of a sample of pisolithic bauxite. The degradation may follow one of three different pathways but, in most cases, all three operate together: (1) discoloration by removal of the iron content of the böhmite-bearing material, (2) alveolization of the matrix by removal of loosened solid material, and (3) crystallization of gibbsite at the expense of the böhmite. The degradation is generally more advanced in the interstitial matrix than in the inner part of the pisoliths. At the right edge of the photograph, part of the dark red böhmite-rich matrix has been discolored and replaced by very porous iron-free böhmite. That transformation does not affect the pisolith. The nucleus of the pisolith has not undergone any transformation, and its opacity and its network of fissures are not disturbed. The microlaminated cortex is only partially disjointed by a discontinuous concentric open fissure, which divides it in irregular scales. In most cases, the development of the discoloration process is strongly influenced by textural distributions. Matrix material is preferentially discolored; consequently, dark red pisoliths may be maintained within a whitish discolored matrix. Samples of bauxite in which pisoliths are preferentially discolored are much rarer. The cortex that surrounds them probably offers resistance and an effective protection against the internal discoloration of the nucleus.
The lower photograph is a macrophoto of a polished slice of a sample of partially discolored pisolithic bauxite. It shows the irregular distribution of the discolored areas. The original bauxite was uniformly dark red in color, and the slightly darker pisoliths were barely distinguishable from their surrounding matrix (C3, D5). Most of the bauxite has been discolored; in these areas, both pisoliths and matrix are equally discolored. In the transitional areas, the matrix may become completely discolored, whereas the pisoliths still exhibit either their original coloration, with both nucleus and cortex dark red in color or with dark red nuclei surrounded by a discolored cortex. A study of the slice shows that the matrix is the most unstable material, whereas the nuclei are the most stable components of the bauxite.

The lower illustration shows the detail of the discoloration in a transitional area: the nucleus of the pisolith (C3) maintains its dark red coloration, whereas part of its cortex is discolored. The second pisolith (A1) is not discolored. The matrix is iron-free in most of the field of view. In the lower right part (E5), however, it has maintained its original aspect. Note that the nucleus of the partially discolored pisolith has many newly formed concentric and radial fissures.
Partially discolored pisolithic bauxite

Dagolili, Lakota
Côte d'Ivoire
Sampled by B. Boulange
Depth: 0.8 m

Objective: × 1.6
PPL and XPL

The discolouration of pisolithic bauxite does not always follow the boundary between the pisolith and the matrix. Here, the discolouration front is abrupt and without any transition. Both nucleus and cortex are cut, but the convex shape of the colored part of the nucleus seems to indicate that the nucleus is somewhat more resistant than the cortex. The general macrotextures are well preserved, and the external margin of the whole pisolith can be easily visualized, both in its colored and in its discolored parts. Even the microtextures by which the nucleus is easily distinguished from the cortex are clearly maintained in both parts of the pisolith. The thinly laminated texture of the cortex and the irregular network of fissures in the nucleus are perfectly maintained.

The böhmite content of the pisolith is maintained undisturbed in both colored and discolored parts, whereas in the matrix, the böhmite is partly replaced by coarse crystals of gibbsite. Small particles of gibbsite and a concentric fissure filled with gibbsite are seen, under XPL, within the pisolith. The section is thinner than usual, making it possible to see the distribution of hematite in the undiscolored part of the nucleus. The cortex, with its yellowish hues, seems to be richer in goethite.
The photomicrograph shows a spherical pisolith that has been completely discolored, yet maintains its original texture. The surrounding matrix has been largely replaced by a crystalliplasma of gibbsite associated with residual pores. The nucleus is small, and surrounded by a very thick composite cortex composed of several successive layers in which the radial fissures are unequally distributed. The outermost laminae are much less fissured than the internal ones. The discoloration of the pisolith allows the textural details of the internal laminae to be clearly distinguishable. In contrast, in the original dark red pisoliths, such details are completely masked by the opacity of both nucleus and cortex. The unequal distribution of the fissured layers of the cortex suggests that during its former history, the pisolith underwent phases of erosion, transport and deposition in several successive matrices. Possibly only the last, unfissured part of the cortex formed within the matrix in which the pisolith is now found. These successive steps of erosion - transport - deposition are corroborated by an examination of several of the following photomicrographs. Note that under XPL, some radial fissures, and parts of the concentric fissures, are filled by a newly formed crystalliplasma of gibbsite.
ALLOGENIC PISOLITHS IN BAUXITE
Lower slopes of the Dietka Bocca, Toumodi, Côte d'Ivoire
Sampled at soil surface
Magnification: × 2

ALLOGENIC PISOLITHS IN PISOLITIC BAUXITE
Lakota, Côte d'Ivoire
Sampled at soil surface by B. Boulange
Objective: × 2.5
PPL

THE UPPER PHOTOGRAPH is a macrophoto of a polished slice of a sample of bauxite containing allogenic pisoliths. The heterogeneity of the included nodules (A3, B5, E5), and the presence of a complex residual rounded fragment of a true and typical pisolitic bauxite (C3), show that all the nodular components have been transported before being deposited in a soft matrix, which was later indurated. The dark-colored nodules are all well rounded. Some of them are true pisoliths with nucleus and cortex, others are rounded fragments of iron-enriched nodules and alterorelics without a well-formed cortex, which seems to prove that the cortex around each true pisolith also was formed before its transport and deposition. A more careful examination of the isolated pisoliths shows that in most cases, their cortex has lost its round shape by erosion.

The lower photomicrograph, and the following ones, show discolored pisoliths that obviously have been broken before being surrounded by a later cortex, which is discordant both on the broken nucleus and on its eroded previous cortex. Even the last-formed cortex has been partly eroded. The fact that the three broken pisoliths shown are in contact shows that they result from the deposition of detrital allochthonous pisoliths, and not from the in situ degradation of the bauxite.
This illustration and the next one show a subrounded pisolith in which most of the external cortex is obviously discordant with respect to a previously formed complex nodule, which is itself composed of a broken nucleus surrounded by its own first cortex. The external matrix is largely degraded. The complexity of the internal texture of the whole pisolith corresponds to the complexity of its evolution during the successive steps of the erosion—transport—deposition processes. The chronological history can be reasonably reconstituted by careful examination of the successive shapes and of the unequal distribution of its micromorphological features.

(1) A first homogeneous and unfractured nucleus is formed within a soft matrix, now eroded. Both nucleus and matrix are dark red, as is usually observed in such parental material for pisolitic bauxite.

(2) This first well-rounded nucleus is surrounded by a first cortex according to an accretion process. During this first step of cortification, the nucleus, but not the cortex, is cut by a first network of radially arranged fissures.

(3) The well-rounded pisolith is released from its erodable matrix and transported, during which period it is broken into several fragments, each of them containing a part of the nucleus and a part of the cortex that surrounded it.

(4) One of these fragments, which is now in the central part of the photograph, is embedded in a second soft matrix and surrounded by a second cortex. During the cortification, the nucleus and the first-formed cortex are abundantly fractured by numerous radial and concentric fissures.

(to be continued on the next page)
(5) This complex pisolith is again released from its matrix, is displaced and broken, is eroded and then redeposited in a third matrix, in which a third cortex is formed. During this last crystallization, the entire complex composite "nucleus" is microfractured by a new generation of radial fractures, which are clearly visible, but less abundant, in the second-formed cortex.

(6) The last-formed cortex, the third one, is continuous, surrounds the entire broken pisolith, and does not show any traces of erosion and transport. The matrix that is now observed around it is the last soft matrix in which the pisolith was deposited.

(7) A long period of time, without erosion or displacement, is then necessary to promote the progressive induration of the interstitial matrix, which loses its silicate components to newly formed böhmite. The pisolitic bauxite is formed, and it will remain untransformed for millions of years.

(8) After that long period of geochemical and geomorphological stability, the matrix and the included pisoliths have more recently become discolored, which allows one to interpret the details of the previously formed microtextures.

(9) The matrix is now degraded, its content of böhmite is replaced by peripheral crystallaria or gibbsite (clearly visible under XPL), and deposits of böhmite microparticles that coat the internal dissolution-induced pores. The böhmite constituent of the first-formed nucleus and of its successive cortices seems to be more resistant to that last degradation, and no gibbsite crystallaria are formed within these domains.

(10) More recently, this sample of bauxite was cut; a thin section allows the chronological events of its history to be reconstructed, at least partially.
PISOLITHS IN BAUXITE

ALLOGENIC PISOLITHS IN PISOLITIC BAUXITE
Lakota, Côte d'Ivoire
Sampled at soil surface by B. Boulangé
Objective: x 2.5
PPL

ALLOGENIC PISOLITHS IN PISOLITIC BAUXITE
Lakota, Côte d'Ivoire
Sampled at soil surface by B. Boulangé
Objective: x 1.6
PPL

Bauxite samples from Lakota show fragmented complex nuclei later surrounded by a continuous, unfissured cortex. The main characteristics of their internal textures are comparable to those that have been previously described. The internal composite nucleus, which consists of a fragmented true nucleus surrounded by its own cortex, is highly fractured by an irregular network of fissures, whereas the more recently formed cortex is not fractured. A first layer of the complete rounded cortex, which appears, in the second photomicrograph, as a slightly fractured one, may indicate that this pisolith has had a somewhat more complicated history than the pisolith of the first photomicrograph. Both samples are completely discolored, and the interstitial matrix is more or less degraded, with formation of residual pores and various deposits of bólunite and gibbsite. The gibbsite coating is clearly visible in the upper right corner of the first photograph.
In samples of allogenic bauxite, well-rounded pisoliths may be formed by successive cortifications around an irregularly shaped nucleus. The shape of the nucleus and that of its surrounding cortex are very similar to those observed in a previously described example (cf. 564). A triangular fragment of a displaced nucleus was surrounded by a thick cortex, whose early lamina- tions gradually give way to more and more circular external lamina- tions. The inner network of fissures is restricted to the inner part of the nucleus and to the first-formed layer of the cortex. The interstitial matrix is highly degraded, and large pores are formed by dissolution or by erosion of the bōhmite of the matrix. Mechanical deposits of eroded material are not visible in the pores, as is the case for other samples (cf. 576, 577, 578, 579, 580 and 581, for example).
Both photomicrographs, the first one in PPL and the second one under XPL, show the perfect geometrical shape of a fragment of pisolith. Its shape and the fact that it fits tightly among other pisoliths obviously show that this feature has not been formed in situ, and that the pisolithic bauxite is an allogenic material, in which most pisoliths were previously formed in a different environment. The böhmite-rich character of the fragmented pisolith is well expressed by its cryptocrystalline aspect, practically isotropic under XPL. The very small specks within the cortex and within the nucleus of the fragmented pisolith, appearing as greenish white dots under XPL, are minute crystals of böhmite. Thin lineaments of secondary böhmite also are observed as infillings of discontinuous concentric fissures, whereas small areas of micro-aggregated crystals of böhmite appear mainly concentrated in the fragment of the first-formed nucleus and randomly scattered within the interstitial matrix. The böhmite-rich matrix has been largely replaced by secondary gibbsite, whose coarse crystals are randomly distributed and intimately associated with the microcrystalline aggregates of böhmite.
EVOLUTION AND DEGRADATION

First stage: iron depletion in the bauxite

The first stage of degradation of pisolith-bearing bauxite involves a process of iron depletion that maintains in situ the aluminous minerals such as boehmite, which may be associated with small amounts of gibbsite. This mineral is rare in the pisolitic bauxites of the first and second generation, but is more abundant in degraded bauxite, in which porosity develops and much more water is available. The increased porosity promotes the formation of gibbsite at the expense of the less hydrated boehmite.

The internodular matrix is generally the first part of the bauxite to be discolored. Red pisoliths are commonly observed in pisolitic bauxite whose internodular matrix has been completely bleached. Nevertheless, and as a general rule, even though the matrix is really the most easily bleached material, the discoloration of the nuclei and cortices follows after only a short delay. In a decimetric sample, for example, all shades of discoloration can be observed together. As is clearly shown in photomacrograph 556, red pisoliths occur commonly within a bleached matrix, whereas the converse phenomenon is never observed. In contrast, the goethite-rich cortices seem more susceptible to discoloration than the nuclei that they envelop.

The discoloration can either preferentially follow the cortex, temporarily avoiding the nucleus, or cut the whole pisolith with sharp and contrasted boundaries between the colored and discolored areas of the pisolith. Where the removal of iron is advanced, the inner textures of the pisolith become particularly clear and identifiable. Comparison with unbleached pisoliths shows that the textures have not been modified by the process of removal of iron. The internal textures of the pisoliths and their external shapes, whose details are clearly seen in the bleached areas, show the obvious allochthonous origin of these pisoliths in the bauxite of the second generation.

Second stage: alveolization of the internodular matrix

The second step in the degradation is progressive alveolization of the internodular matrix, destabilization of the pre-existing microcrystalline boehmite, its replacement by macrocrystalline gibbsite and amorphous material and, in some cases, relative accumulations of small amounts of iron originally linked to the boehmite-rich areas. The interstitial matrix becomes markedly porous. That new porosity results from the combination of two competing processes, on one hand, dissolution and leaching of part of the aluminum content and, on the other, mechanical transfer of microparticles of boehmite released by the removal of their ferruginous cement. These microparticles of boehmite and amorphous materials may be deposited in alveolar pores in the subjacent bauxite. The macrocrystalline gibbsite is concentrated in compact banded textures that are mainly distributed concentrically around the pisoliths or as a rim or coating around the newly formed alveolar pores. Macrocrystalline (>500 μm) and mesocrystalline (50–500 μm) gibbsite also appears within the concentric fissures formed in the thickness of the cortex or at the contact surface between it and the central nucleus.

Third stage: destruction of the pisoliths

Thereafter, the replacement of the original boehmite by gibbsite invades the inner part of the pisolith. A curved and crescentic pore, with thin arborescent margins, develops within the cortex. This pore is coated by a rim of gibbsite crystals and by a diffusion halo of iron that was excluded from the "gibbsitized" volumes.

While alveolization of the internodular matrix is proceeding, the more and more isolated and vulnerable pisoliths also begin to be degraded; they experience loss of material, formation of internal pores interconnected by an intricate network of channels, which follow the pre-existing radial and concentric fissures, and development of gibbsite as a coating around the newly formed pores. The internal textures, which until now allowed the cortex and the nucleus to be clearly distinguished from each other, are finally replaced by simplified textures in which only the spherical shape of some volumes allows the presence of pisoliths to be identified as isolated features within a highly porous and completely disrupted and disfigured matrix.

Fourth stage: infilling of the pore volumes

The pores and alveoles, which developed firstly in the matrix and secondly in the pisoliths, are infilled by a fine detrital material whose microstratified habit and strongly oriented distribution are obviously related to gravitational processes. The orientation of the infillings of adjacent degraded pisoliths is constant, and the influence of a gravity-controlled process is confirmed. These infillings are essentially composed of micro- and cryptocrystalline boehmite and amorphous material, to which is associated variable but minor amounts of iron.
oxyhydroxides, responsible for their beige or orange-yellow color.

These deposits are subjected to frequent reworkings, by internal erosion followed by new phases of deposition, simulating, in this manner, a fitted organization similar to that of a cut through river terraces (photo 580). The internal textures of the pisoliths are quickly obliterated, and the capricious course of the channels and of their infilling materials soon makes them unrecognizable. Some pisoliths, avoided by the internal erosion and by the further infillings, may have been completely replaced by gibbsite crystallaria*, with conservation of the former microtextures and radial fissures, which localized the first steps of the gibbsite formation. The pisolith exhibits a septarian internal texture that is very comparable to the septoalteromorphic texture displayed by weathered grains of feldspar. In this particular case, the term "pseudoalteromorph" can be used, since it is not an alteromorph but a particular textural feature that exhibits an appearance very similar to that of a true alteromorph.

The downward transfer of böhmite and amorphous materials as detrital particles, in the profile or along the slopes, may be sufficiently important to reach the alveolar pores of the lower isalteritic or alloteritic lateritic covers. These detrital accumulations of micror crystaline böhmite may later be destabilized and replaced by macrocrystalline gibbsite. These accumulations may be observed as infillings of pores even in the horizons of unbleached pisolitic bauxite, whose alveolar degradation has only reached the interstitial red matrix. Accumulations of detrital crystals of gibbsite are in some cases observed in pedotubules excavated by soil microfauna within near-surface bauxite.
**COMPLETELY DISCOLORED PISOILITIC BAUXITE**

Lakota, Côte d'Ivoire
Sampled at soil surface by B. Boulange

Objective: x 1.6
PPL and XPL

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The microstructural and evolutionary features shown in these photomicrographs are very similar to those of the previous illustrations. The additional feature consists in a crescent-shaped area of the cortex of the main pisolith, whose bōhmite content has been replaced by a residual pore surrounded by an irregular and dendritic network of gibbsite crystalliplasma. This crystalliplasma is in contact with the surrounding matrix and with a neighboring pisolith (A4–5), which has been completely replaced by a large pore in which aggregates of secondary products are irregularly scattered. A continuous peripheral fissure is formed in which a gibbsite crystalliplasma is well developed. Each pisolith is surrounded by a similar peripheral crystalliplasma and, in the contact areas between two neighboring pisoliths, bridges are formed. Continuous complex gibbsite-rich cortices are formed; these can isolate pyramidal volumes of the surrounding matrix (A2, B5) according to a process very similar to that previously described concerning the evolution of the iron crusts (cf. 536, 537, 545, 548 and 549). The surrounding matrix has been partially dissolved, and its bōhmite content has been replaced either by a gibbsite crystalliplasma or by imported ferruginous material. It is probable that the iron of the irregular ferruginous halo, which surrounds the dendritic crystallaria, has been imported via solutions and has diffused in the surrounding parts of the bōhmite-rich matrix.
The photomicrographs show an advanced stage in the textural transformation of a pisolith. The original textures of the nucleus and of its cortex are well preserved in a large part of the pisolith, in which the network of fissures and the laminated microtexture of the cortex are clearly recognizable. The mineralogical composition is not yet modified in the pristine part of the pisolith. In its lower part, the pisolith has had its original textures partly modified by alveolization and by the progressive replacement of its bôhmite content by deposits of gibbsite that regularly coat the walls of the pores, of the channels and of the fissures. The degradation of the interstitial matrix is much more advanced than that of the pisolith.
576, 577

DEGRADATION

show the highly complex microtextures that progressively develop within a degraded, discolored pisolith. In this last step of degradation, the textures of both pisoliths and interstitial matrix are modified in such a way that (1) large pores develop by dissolution or by internal erosion, (2) part of the bôhmite content of the original bauxite is replaced by gibbsite, either as a coating around the pisoliths or as a thin interconnected network of gibbsite within the pisoliths, and (3) fine-grained materials are deposited by internal circulation of water in the previously formed pores. A very complex texture results. As long as the thick framework of gibbsite is maintained, the meso- and macrotextures of the bauxite are well preserved. It can be seen, in PPL, that the microlaminated deposits of fine-grained materials are all oriented parallel to each other, whatever may be their location, either within the matrix or within the pisoliths. The pores are generally of sufficient size for filling to occur by gravity. The rotation of the microscope stage has been chosen in such a way that all deposits appear with a naturally horizontal orientation. Under XPL, the thick peripheral deposits of gibbsite around the pisoliths are clearly distinguished from the thin irregular networks formed within them.

PART 4: LITHORELICS, ALTERORELICS, NODULES AND PISOLITHS
The degradation of the interstitial matrix has promoted the formation of gibbsite-rich banded crystalliplasmas, mainly developed at the contact with the pisoliths. These peripheral crystalliplasmas are composed of coarse-grained gibbsite crystals, which form a continuous banded texture around each pisolith. The pisoliths are very commonly closely spaced in the matrix, and they may be welded together by bridges of coarse gibbsite crystals. All these banded structures are progressively interconnected to each other, as matrix is degraded, and as more and more numerous crystalline bridges are formed. All these interconnected banded textures progressively form a mechanically and geochemically resistant framework, in the cells of which only the pisoliths and some residual parts of the matrix have a sufficiently soft internal texture for easy erosion by mechanical processes. The relict bohmite-rich parts are progressively either replaced by new generations of gibbsite crystals, or mechanically eroded. In the first case, very contorted and sinuously banded deposits of fine-grained crystals are formed gradually as dissolution-induced pores are formed. In the second case, very finely textured materials are transported and deposited as coatings and infillings in the previously formed cavities. Within these coatings, deposited by gravity, the bohmite-rich character of the material is not changed; it is slightly mixed with iron oxyhydroxides, which cause the characteristic coloration and emphasize their regular microstratifications.
The photomicrographs show two examples of a very advanced stage of the degradation of a pisolith. Photomicrographs prepared with XPL are not shown because the textural relics of the böhmite-rich parts are not informative (these areas are nearly isotropic), and because the gibbsite-rich peripheral coatings, with their characteristic texture and distribution, were previously illustrated. The upper photomicrograph shows a relatively simple case of the replacement of a pisolith by a large internal pore partially filled by gravitational deposits of böhmite. The internal laminations of these deposits are organized as alluvial deposits in fluvial terraces; part of the previously deposited materials are evacuated, by the flow of water in circulation, before newly formed detrital materials are deposited. Some irregular but characteristic remnants of the original material have been temporarily maintained (D2, D4).

The lower photomicrograph shows a more complicated case of the replacement of a pisolith in which the original network of fissures has been infilled by resistant deposits of gibbsite. This septa-like texture has a behavior comparable to a resistant boxwork, in the pores of which laminated deposits of böhmite may occur.
These photomicrographs show the final stage of degradation of a pisolith. The earlier stage was certainly very comparable to the case in photomicrograph 581. Most of the septa of gibbsite are maintained, whereas all internal volumes, previously filled by boehmite (either directly inherited or of detrital origin), have been replaced by gibbsite crystalliplasmas. This newly formed internal texture is likely comparable to the texture of the glomero-septo-alteromorphs, which are developed, under conditions of ferrallitic weathering, as a result of the degradation of feldspar-group minerals. This special case illustrates what can be termed a "pseudo-alteromorph"; it is not an alteromorph, but a textural unit that seems to be an alteromorph. The prefix "pseudo" used here is entirely justified to allow a distinction from the true alteromorphs (pseudo-morphs and not pseudo-alteromorphs) developed at the expense of euhedral crystals.
Photomicrographs of discolored pisolithic bauxite show an advanced stage of the degradation of the interstitial matrix. Each volume of the matrix is surrounded by the thick peripheral crystallaria of coarse-grained gibbsite that coat the neighboring pisoliths. The original inherited böhmite has been replaced by deposits of böhmite exhibiting cross-laminated textures. Parts of these deposits are finally destroyed by dissolution. Irregular residual pores are formed; they are coated by thin crystallaria of fine-grained gibbsite.
The microphotographs show that the finely crystallized böhmite, which was eroded and transported from the degraded upper pisolith-bearing horizons, can be redeposited within the pores and cavities in the lower horizons of isalteritic or alloteritic bauxite. The authigenic matrix, which is mainly composed of well-crystallized gibbsite associated with small patches of more ferruginous composition, exhibits many large and irregular pores, whose volume is now occupied by microlaminated deposits of böhmite. The böhmite, whose end-member composition is $\gamma$-AlO(OH), is naturally colorless. However, in these deposits, it is commonly colored by iron oxyhydroxides, whose relative concentration determines the variable coloration of the successively deposited layers of böhmite-rich material. More recently formed fissures and pores, both within areas of böhmite (D4) and matrix volumes (A3), are coated by thin layers of gibbsite microcrystals. The böhmite-rich main central area is partially surrounded by a thicker layer of gibbsite macrocrystals, formed at the expense of the matrix during a period of time when the main pore was empty and free of the böhmite deposits. These coarse-grained crystals have the same origin as the peripheral coatings of coarse-sized gibbsite in the upper pisolith-bearing horizons.
MICROLAMINATED DEPOSIT OF BÖHMITE-RICH MATERIAL

Old bauxitic crust
Diedka Bocca, Toumodi,
Côte d'Ivoire
Sampled at soil surface
Objective: x 6.3
PPL

This photomicrograph shows a detailed but very partial view of a large pore in a sample of bauxite. The pore has been infilled by microlaminated deposits of böhmite. The first-deposited microlaminae show a repeatedly decreasing coloration, similar to a graded bedding. The last-formed laminae are much enriched in iron and dendritic manganese oxides. Large crystals of böhmite are never seen in unmetamorphosed aluminum-rich rocks; in bauxite originating from the superficial weathering of aluminous rocks, the böhmite crystals are so fine grained that the mineral is not identifiable by optical methods only. X-ray powder-diffraction patterns are necessary for a positive identification when the mineral is observed for the first time by an unexperienced soil scientist. The typical association of böhmite with gibbsite and hematite, as well as the environmental conditions under which the bauxite samples were collected, generally provide valuable aids in the identification of böhmite.
These photomicrographs show the later evolution of a microlaminated deposit of böhmite-rich material in an outcrop of bauxite exposed to conditions of superficial weathering. The böhmite-rich deposits are irregularly destroyed by the formation of irregular pores, channels and embayments, which are soon filled by mesocrystalline gibbsite. These crystals of gibbsite are formed at the expense of böhmite, which they replace by a hydration process. The areas of gibbsite are perfectly colorless, and the iron, previously associated with the böhmite-rich material, does not enter the gibbsite structure. It is locally concentrated, and forms irregular, dark-colored impregnation halos around the colorless crystallarias of gibbsite. Gradually, as the böhmite-rich material is replaced by newly formed crystals of gibbsite, the original or inherited textures are obscured, and become less and less recognizable. All types of böhmite-bearing secondary materials undergo such textural transformations, being progressively replaced by a new generation of gibbsite; the pisolithic bauxites, which are usually böhmite-rich and which exhibit particularly recognizable textures, can be gradually transformed into gibbsite-rich material by the replacement of both textural components, the pisoliths and the interstitial böhmite matrix (see earlier illustrations). Such replacement promotes the disappearance of the previously acquired pisolithic texture.
Even the compact red material of the interstitial matrix of typical pisolitic bauxites can be partially eroded; the residual pores can be later infilled by allochthonous böhmite-rich materials that have lost an appreciable part of their ferruginous components, which leads to a particularly sharp contrast between the discolored detrital deposit and the dark red pisoliths and undisturbed residual matrix. The pisolith at the right of the photomicrograph clearly shows the characteristic textural patterns of most original pisoliths: a well-rounded nucleus is criss-crossed by radially and concentrically organized fissures, whereas the thick cortex is slightly fractured by radial microfissures. In the contact area with the böhmite-rich deposit, the cortex of the pisolith has been partially eroded.
The photomicrographs show a relatively rare feature, a detrital deposit of gibbsite crystals in a tubular pore, possibly created by microfauna activity. The photos were taken in an orientation suitable to better show the regularity of the curved successive deposits of elongate crystals of gibbsite, which are all oriented parallel to the natural orientation of the laminated detrital deposit. The small interstitial volumes between the crystals are infilled by reddish brown deposits of fine material, originating from the matrix of the bauxite. Elongate crystals, where mechanically deposited in a pore, are invariably oriented parallel to the bottom of the pore; where elongate crystals are chemically deposited, they are invariably preferentially oriented perpendicular to the walls of the pore, as has been shown in the earlier photomicrographs. These elongate crystals of gibbsite probably originate from the dislocation of a chemically formed layer of gibbsite crystals, as previously shown, by dissolution of their ferruginous cement. The photomicrograph under XPL is necessary to show that the colorless elements, under PPL, are not elongate empty pores, but really are fragments of gibbsite crystals. The now infilled tubule is itself partially formed within a larger volume of coarse crystals of gibbsite. Some euhedral crystals of gibbsite are partially separated from their original matrix, and they seem to be falling from the upper part of the chamber (B2), in the way rock fragments naturally fall from the roof of a cavern.
DETERTAL DEPOSIT OF GIBBSITE CRYSTALS
Old bauxitic crust
Orumbo Bocca,
Toumodi, Côte d’Ivoire
Depth: 0.4 m
Objective: × 10
PPL and XPL

This photomicrograph shows another biopedotubule that cuts a ferruginous matrix in bauxite and that is irregularly infilled by well-oriented elongate crystals of gibbsite mixed with irregular volumes of dark ferruginous deposits. The surrounding matrix has the usually observed makeup of such alloteritic bauxite: irregular polymineralic patches of randomly oriented autochthonous crystals of gibbsite (A3), round areas infilled by allochthonous chemically formed and regularly oriented crystals of gibbsite surrounding inner infillings of red-colored material (B5) and, finally, a microcrystalline hematite-rich matrix (A4, C5) that contains the previously mentioned features.
Secondary Oxides and Hydroxides

A FEW PHOTOMICROGRAPHS are collected together in this last part of the book in order to exhibit characteristic secondary minerals, namely the hydroxides and oxides of aluminum, iron and titanium. These minerals are commonly observed in thin sections of bauxite and iron crust, less commonly in alterites and soils. These photomicrographs were selected to give particularly illustrative examples of crystallized material coarse enough so that their habit and main morphological properties (e.g., extinction, cleavages, arrays of twinned domains, shapes, arrangements) are clearly visible. The main micromorphological characteristics of these minerals are given in the captions.

Well-developed crystals of gibbsite, concentric associations of hematite – gibbsite – goethite, of hematite – goethite and of coarse crystals of goethite only are commonly observed within bauxitic and iron crusts subjected to late processes of absolute accumulation. These minerals develop either as crystallaria* (mainly gibbsite) or as simple or complex coatings* that partially or completely infill the pores, cavities and channels developed by various geochemical and biological processes. These include dissolution, alveolization, recrystallization, and excavation by the microfauna.

Coarse-sized crystalplasmas of secondary titanium oxide, mainly anatase, are rarely observed in most alterites, soils and ferruginous or bauxitic crusts. In general, this oxide is either intimately mixed with iron oxide or hydroxide, or it occurs as microparticles whose size does not allow recognition of their mineralogical or chemical nature. It may also form cryptocrystalline assemblages with other oxides of titanium (brookite and rutile), possibly as a pseudomorph after titanium-rich minerals. These cryptocrystalline assemblages are common as areas of “leucoxene” in the alteromorphs after ilmenite, titanite or perovskite. Only in studies of titanium-rich rocks, such as some nepheline syenites, pyroxenites or carbonatites, could anatase mesocrystals easily be observed, as alteromorphs after perovskite, for example.

Few soil scientists, when studying their thin sections of soils, have the opportunity to observe such well-formed secondary materials. Comparison with these photomicrographs will possibly aid them in the determination of their poorly developed or fine-grained secondary minerals.

Moreover, the entire collection of photomicrographs in this book is offered with the same didactic purposes in mind. The author hopes to have been able to invite soil scientists and other environmentally conscious geoscientists, and to stimulate them, to examine with accuracy and delight, the parent rocks and weathered materials that are concealed, and commonly left unsampled, at the base of their soil profiles.
Bauxite on Birrimian sedimentary rocks
Western Côte d'Ivoire
Sampled at soil surface

Objective: x 4
XPL

596 Gibbsite Crystallaria

Gibbsite crystallaria around a dissolution pore. The undisturbed bauxite is visible in the upper left corner of the first illustration, and along the right side of the second one. The gibbsite crystals are randomly oriented and intimately associated with ferruginous material directly inherited from the parent rock. All around the residual pore, very typical coarse crystals of gibbsite exhibit a strong tendency to be oriented roughly perpendicular to the walls of the void. Most of them are euhedral crystals, at least in the parts that protrude into the empty pore, and they exhibit the commonly observed twinning. The second photomicrograph shows the repeated twins of the gibbsite crystals, leading to pseudohexagonal groups of crystals (B3, D2, D4). Their external shape is somewhat reminiscent of twinned crystals of aragonite. The gibbsite is colorless in thin section and first-order grey in XPL. Its birefringence (0.015–0.030) is somewhat higher than that exhibited by quartz crystals (0.009). Where the thin section is slightly thicker than usual (see also 278), the gibbsite crystals may appear as yellowish grains, whereas the quartz grains are first-order grey. The crystals are monoclinic, biaxial positive, length-slow, and their extinction angle may attain 25°.

597 Gibbsite Crystallaria
The 10-m-thick ferruginous bauxite, which caps the top of the hill (alt. 520 m), is developed at the expense of Birrimian metabasic and diabasic rocks. It covers an argillaceous isalitonic level more than 10 m thick; the parent rock is rarely observed at the base of the weathered profiles. The bauxite is composed of randomly oriented microcrystals of gibbsite, intimately associated with inherited ferruginous components. It is visible along the lower part of the photomicrographs. The pores, which are randomly distributed within the matrix, are due to local dissolution of the matrix minerals. Microlaminated deposits regularly coat the walls of the pore. Several successive and interstratified deposits of red-colored hematite and colorless gibbsite may alternate. The residual central pore is generally occupied by an infilling of well-formed crystals of goethite. All these deposits seem to originate from allochthonous aluminum and iron, leached from the upper parts of the profile, and transported in solution by percolating water. Nevertheless, a different hypothesis has been suggested by Boulangé et al. (1975). They attribute the composite thick layer of alternating hematite and gibbsite to a desilication process of a previously introduced coating composed of ferruginous kaolinite. Under these conditions, only the central goethite-rich part is considered to be of truly allochthonous origin.
A magnification, shows that the previously suggested hypothesis of the desilication of a pre-existing kaolinic coating does not seem to be quite satisfactory to explain the detailed morphology of the contact areas between the successive internal layers. In reality, at the bottom of each hematite-rich layer, the contact with the following layer of gibbsite crystals exactly molds the euhedral shapes of the crystal terminations, as if the successive deposits alternated with a period of quiescence, during which a crystallaria of uncovered crystals was formed. The deposit of the hematite-rich layer penetrates somewhat between the indentations of the previously formed layer of euhedral crystals of gibbsite, and this phenomenon is repeated in the most central, and most recent, gibbsite - hematite double layer. In contrast, the contact between hematite and gibbsite exhibits the usually smooth and regularly curved shape typical of a true mechanical deposit of fine-grained particles. A very thin concentric layer of well-formed crystals of gibbsite is even clearly visible within the thick hematite-rich deposit. In contrast, the second photomicrograph exhibits a morphology that seems to better correspond to a desilication process. The hematite-rich layers are discontinuous and crescent-shaped, and the central part of the tube is infilled by illuviated material, as yet untransformed.
**SECONDARY OXIDES AND HYDROXIDES**

**602**

**Composite cutanic deposit**

Old ferruginous bauxite
Orumbo Bocca,
Toumodi, Côte d'Ivoire
Sampled at soil surface

Objective: x 10

XPL

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**603**

**Goethite infilling**

Old ferruginous bauxite
Orumbo Bocca,
Toumodi, Côte d'Ivoire
Sampled at soil surface

Objective: x 6.3

XPL

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The upper photomicrograph shows a well-crystallized composite infilling of a dissolution pore. Several alternating thin layers of gibbsite and hematite form the lower part of the photograph, whereas a large infilling of well-crystallized goethite is seen in the upper part. Note the shape of the goethite crystals; they crystallized as fibrous and curved units, forming a compact and homogeneous assemblage, without any residual pores or material between them. The photograph was taken under XPL; the deep yellow color of the goethite (under PPL) entirely masks its birefringence colors. Only the fibrous material that is parallel, or nearly so, to the cross-hairs of the ocular lens are at extinction, which shows that the photograph was taken under XPL. Note that the fibrous crystals of hematite, in the thickest central layer, conform to the crystallographic orientation of the fibrous crystals of goethite. This particular feature could correspond to a later epitaxial replacement. The lower photomicrograph shows a complete section cut perpendicularly to the main axis of the tubule. Only one layer of hematite is visible; it surrounds a central part that is fully infilled by crystals of goethite of similar habit as in the earlier photomicrographs. Along the four sides of the photograph, parts of the iron-rich (E2) and aluminum-rich matrix of the bauxite are recognizable.
A pore has formed within an iron crust. The matrix of the crust is composed of fine hematite and goethite, which are diversely indurated. Quartz grains originally included in the matrix were completely dissolved, leaving residual pores (C1, C5). The large tubular pore, and also the small interstitial pores that formed between the aggregates of plasma that make up the matrix, are now partially infilled by regular thin deposits of well-formed crystals of goethite. The upper photomicrograph (PPL) clearly shows the successive coatings, which all are regularly crescent-shaped. Some intercalations of red detrital material are visible in the lower part of the composite coating, whereas each lamina is separated from the previous one by a thin, smooth and dark border.

The lower photomicrograph (XPL) shows the perfect orientation of the goethite crystals, which have grown perpendicular to their support. In the first-formed layers, the crystals are perpendicular to the walls of the cavity, but gradually, as the cavity became infilled, the curvature of the crystalline deposit is modified in such a way that the thin crystals are always oriented perpendicularly to the adjacent previously formed layer. The grey-colored areas are due to the particular orientation of the individual crystals; they are supported by walls whose orientation is parallel to the optic planes of the microscope.
SECONDARY OXIDES AND HYDROXIDES

606, 607

**Absolute Accumulation of Goethite in Iron Crust**
Embu-Guaçu, SP, Brazil
Sampled by S.R. Soares Silva Vieira

Objective: x 16
PPL and XPL

The upper photomicrograph (PPL) and the lower one (XPL) show the characteristic shapes and colors of coarsely crystalline goethite. It formed by in situ crystallization from percolating iron-bearing water. The crystals are needle-shaped, and they exhibit a coarser size and greater thickness than the fibers of goethite in earlier photographs.

In the lower photomicrograph, the alternating interference-colors exhibited along the needles may indicate that the goethite deposit is composed of several successive layers, simulating a regular true banded texture. However, this habit also could be due to a torsion of the needles during their growth, as is the case in the apparently banded structure of chalcedony deposits in vesicles in basalt. Note that the second-order colors of the goethite crystals are partly masked by their own deep yellow natural color. The goethite, α-FeO(OH), is orthorhombic and biaxial negative.
Both photomicrographs show, under PPL and under XPL, respectively, the radiating arrangement of goethite crystals, as it appears in a section cut more or less parallel to the walls of the pore. This orientation is consequently more or less perpendicular to the orientation of the sections shown in earlier illustrations. All radiating units are joined together according to a regular network of suture lines, which shows some similarities to the commonly observed polygonal granular texture. Within each radiating unit, all needles are oriented radially around a center (D4), and the regular black crosses appearing under XPL are the sign of a well-ordered system of radiating fibers. The regularity of the texture, as seen in a thin section, evidently depends on the external support on which the needles began their crystallization. Well-radiating sheafs can be cut, by the plane of the thin section, in an oblique direction that makes the well-ordered radiating texture disappear. The two uncolored areas of the top photomicrograph are holes due to plucking during the preparation of the thin section.
RELATIVE ACCUMULATION OF TITANIUM OXIDE within an alteromorph after perovskite
Tapira, MG, Brazil
Depth: 1.5 m
Objective: × 6.3
XPL

A complex of microcrystals of anatase (TiO₂) results from the complete weathering of a grain of perovskite (CaTiO₃) in the upper part of a ferrallitic profile. The resulting entity is an ortho-alveoporo-alteromorph. The randomly distributed empty areas are residual voids developed by the partial dissolution of the primary mineral. They do not result from the further evolution of the alteromorph. This observation allows the alteromorph to be classified as an ortho- and not as a para-alveoporo-alteromorph. Around large residual voids (C–D1), probably interconnected with transmineral pore-space, and along irregular intramineral fissures, complete elimination of the soluble primary elements and optimal circulation of water have resulted in the best conversion of the titanium oxide into mesocrystals of anatase. Their size and bright yellow color clearly contrast with the brownish orange color of the cryptocrystalline background. Examination of unweathered perovskite, in the lower levels of the profile, shows that most areas occupied by perovskite are either highly fractured large single crystals or aggregates of distinct smaller crystals. This last distinction, even in the case of unweathered minerals, is not always obvious because the pseudocubic nature of the perovskite crystals makes these appear nearly at extinction, between crossed polarizers, whatever the orientation in the plane of the thin section. Irregular alignments of mesocrystalline anatase suggest the occurrence of a network of intramineral fissures or of intermineral boundaries. These have played the same role as residual voids, and have locally resulted in enhanced crystallinity of the secondary product. Such well-crystallized titanium-rich alteromorphs allow individualized and characteristically colored crystals of anatase to be clearly observed and identified. Otherwise, such characteristic properties would be indistinguishable, as in most cryptocrystalline alteromorphs of "leucoxene" at the expense of ilmenite and other titanium-rich primary minerals. The surrounding reddish-brown areas are crypto-alteromorphs after clinopyroxene and, possibly, after phlogopite.
References and Bibliography

REFERENCES USED IN THE TEXT


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**ADDITIONAL BIBLIOGRAPHY CONCERNING THE SAMPLES DESCRIBED**


ALTERITE
The term *alterite* is used to designate, in a profile, the levels located between the unweathered bedrock and the soil horizons. It generally comprises a lower level in which the original petrographic texture is maintained and still recognizable either in the field or in thin section (*isalterite*), and an upper level in which the original textural features have partly or totally disappeared (*alloalterite*). The weathered part of a profile, in which structures of the original rocks are maintained, is also called *saprolite*.

ARGILLAN
The term is used to designate a cutanic fabric whose mineralogical nature is principally composed of clay minerals. The clay minerals are commonly kaolinite, more or less colored by goethite or hematite (*ferri-argillan*), in ferrallitic soils, or smectite-group minerals (saponite, nontronite) and montmorillonite in the lower parts of landscapes, where the conditions of drainage are less efficient. Argillan exhibits commonly alternating microlaminations of limpid and speckled clay, generally oriented parallel to the surface (wall of a void, skeleton grain or ped surface) on which it is fixed by illuviation and deposition of detrital clayey material.

ARGILLIPLASMA
The term designates the fraction of soil material of colloidal size that consists dominantly of clay minerals. In the arrangement of the elements of a soil, the term *argilliplasma* is complementary to the skeleton grains.

ASEPIC
The term designates a kind of plasmic fabric. The general term *sepic* is derived from separation, so that aspec (with θ = without) means without separation of plasma. An aspec plasmic fabric corresponds to a dominantly anisotropic plasma with anisotropic domains that are unoriented with respect to each other. The terms *argillasepic* and *silasepic* designate a fabric of a plasma dominantly composed of either "anisotropic" clay minerals or of particle sizes with relatively high proportions of silt-size grains so that the domains are difficult to recognize (Brewer 1964).

CHADACRYST
The term is used to designate the relatively small crystals that are enclosed within a larger poikilitic crystal. Chadacrysts of clinopyroxene or plagioclase are commonly observed in poikilitic hornblende, for example.

CHITONIC
This term, introduced by Stoops & Jongerius (1975), pertains to a type of distribution pattern of coarse and fine constituents in which the coarser particles are completely or partly coated by finer material. Such material may be illuviation coatings or random deposits of clay on grain surfaces.

COATING
This term denotes a layer of any substance covering surfaces of voids, grains and aggregates. It was used by Kubiena (1938) to describe colloidal films around grains. Coated grains may be embedded in the groundmass, but the concept excludes birefringent fabrics such as the *granositic b-fabric*.

CRYSTALLARIA
This term was proposed by Kubiena (1938) to designate crystalline pedofeatures composed of single crystals or, more commonly, arrangements of crystals of relatively pure fractions of the plasma that do not enclose the S-matrix of the soil material, but rather form cohesive masses. Their morphology, like small geodes, is consistent with their formation in pre-existing voids in the enclosing soil material. The crystals that form a crystallaria are generally oriented parallel to each other and perpendicular to the walls on which they grow. The crystallaria may be reduced to crystalline bands running around a central empty residual pore, or they may infill completely the original empty pore. The size of the individual crystals is generally sufficient to allow the deter-
mination of the mineral species present by optical methods. The most common crystallaric are composed of calcite, gypsum, gibbsite, goethite, kaolinite, smectite group minerals or quartz crystals.

Cry stallplasma

The term is used to distinguish the portion of the soil plasma whose components exhibit a grain size allowing their distinction as separate anisotropic units. The term is generally used in opposition to the term argillplasma.

Cutan

Brewer (1964) coined this term to designate a modification of the texture, structure, or fabric at natural surfaces in soil materials, due to concentration of particular soil constituents or in situ modification of the plasma. Cutans may be composed of any of the component substances of the soil material. See also: argillan, skeleton, ferran, and goethan.

Enaulic

Stoops & Jongerius (1975) introduced this term to describe a type of related distribution pattern of coarse and fine constituents in which the coarser particles are associated with aggregates of finer material regularly distributed in the interstitial spaces. The aggregates do not completely fill the interstitial pore-spaces. The size of the skeleton grains may be greater or equal to that of the aggregates.

Epigenetic Replacement

The term, or the equivalent, epigenesis, is used to designate the slow replacement, in a rock, at a low temperature and a low pressure, of a mineral or material by another mineral, each added atom replacing a pre-existing atom. This phenomenon is linked to the transfer of chemical elements to a point, or volume. The term metasomatism also is used to designate such a replacement. The chemical elements added either do not exist in the mineral being replaced, or are present there in relatively low concentrations only. In general, the volume and shape of the mineral or material are well maintained during or after the replacement. Examples are provided by the replacement of kaolinite by iron oxihydroxides, of feldspar by calcite, and of calcite in fossilized brachiopods by pyrite.

Ferran

This term refers to a kind of cutan exclusively composed of oxides or hydroxides of iron (or both). This kind of ferran is commonly observed in iron-rich crusts and lateritic bauxites of tropical regions, in which large quantities of mobile iron are locally dissolved, transferred and deposited to form crystals. Ferrans commonly exhibit either linear and banded structures by crystallization in available planar voids (cracks), or concentric structures by crystallization within three-dimen­sional residual voids (see also goethan and hemaan).

Ferr-argillan

This term refers to a kind of cutan composed of variable proportions of clay minerals mixed with iron oxides and hydroxides. Ferr-argillans are the most common kind of cutans in soils and near-surface materials, principally in ferrallitic soils. They correspond generally to deposits of clay particles previously stained by iron compounds and not to synchronous precipitates of clay minerals and iron compounds.

Gefuric

Stoops & Jongerius (1975) introduced this term to describe a pattern of distribution of coarse and fine constituents in which the coarser particles are linked by braces of finer material. The coarse particles are not in contact with each other, and thus have no skeleton function.

Gibbsan

This term refers to a kind of cutan composed exclusively of gibbsite crystals. Several origins of gibbsan (sometimes called gibbsian to avoid any confusion with gypsum) are observed. Commonly gibbsans are formed in situ by crystallization of hydroxide of aluminum from transferred dilute solutions. They may be also derived from the desilication of kaolinate cutans (argillans) previously deposited as detrital particles. More rarely, gibbsans may form by deposits of detrital crystals previously formed in a higher level of the profile and broken and displaced under the influence of biological factors, such as the activity of the soil microfauna. In the two first cases, the gibbsite crystals are oriented perpendicular to the walls of the receptive void, whereas in the third case, the elongate crystals of gibbsite are generally oriented parallel to these walls.

Glæbule

The term, derived from the Latin glæbula = small clod of earth material, was proposed by Brewer (1964) for a three-dimensional unit observed within the S-matrix and whose shape is usually prolate to equant. It is recognizable by its morphology, its greater concentration of some con-
stituents, differences in fabric with the enclosing soil material, and its distinct boundaries. Nodules, concretions, septaria and papules are glabules.

**GLACIS**
The term refers to a gently inclined slope, formed by a geomorphological process characteristic of dry climates, which extends on a mountain side, either from a cliff or around a residual hill, plateau or inselberg. In some cases, it is equivalent to a piemont slope. It is derived by analogy with the glacis used in fortifications as a defense against attack. The inclination of a glacis does not exceed some 5° in its lower part, where the slope may appear as rectilinear and uniform. In its upper part, it is linked to the sides of the mountain, with progressively more and more curved and steeper slopes.

**GOETHAN**
This type of cutan consists exclusively of goethite. It generally results from in situ deposition from dilute solutions derived from the upper parts of the profile or crust, where geochemical conditions may induce the mobility of iron and its transfer to lower portions of the profile. In most goethans, goethite exhibits a very fine fibrous habit. The fibrils grow perpendicular to the walls of the original void. Their bright yellow to orange colors are characteristic and allow easy distinction from other types of cutans.

**GRANOSTRIATED BIREFRINGENCE-FABRIC**
This term, most commonly written granostriated b-fabric, is a soil fabric formed by clay particles oriented parallel to the surface of a resistant fabric units, such as mineral grains or hard nodules. A birefringent halo is seen around the grain or nodule between crossed polarizers when the microscope stage is rotated. Porostriated b-fabric is similar, but found within the matrix all around a pore. Granostriated and porostriated b-fabrics have features in common with hypocoatings.

**HEMATAN**
This type of cutan, composed of hematite, is rather rare in iron-rich crusts and bauxites because it has a tendency to be formed exclusively in very slightly porous and quasi-anhydrous media, as in argiliplasmas and all textures of very fine-grained materials. In iron crusts and bauxites, it is in some instances observed forming regular intercalations with goethans and gibbsans. In these cases, the hematan (oxide of iron) is invariably located near the wall of the pore, or even in the surrounding matrix, where anhydrous conditions prevail, whereas the hydroxides of the goethans and gibbsans are particularly well developed along the walls of large interconnected vugbas, where the circulation of water is more abundant and easy.

**HYPOCOATING**
This pedofeature is distinguished from the most common coating by the fact that it occurs immediately adjoining rather than on the surface with which it is associated. It may arise by impregnation of a groundmass immediately adjacent to the surface of a void or of a skeleton grain (external hypocoatings) or by impregnation of the surface zones of a microporous grain (internal hypocoating).

**INTERTEXTIC**
The term is used to determine a kind of elementary fabric in which mineral grains are united or linked to each other by intergranular braces of finer material (flocculated clays or organic material). This intertextic fabric corresponds to the related gelaric pattern of distribution of Stoops & Jongerius (1975). This fabric gives to the material a large and generally continuous networks of pores.

**MAMMILATE**
The term relates to the shape of protuberances appearing on the undulating and rough surface of a grain. The surface, seen in a section, consists in juxtaposition of convex curved protuberances separated from each other by triangular acute inward boundaries. The term may also be used to indicate coloiform or botryoidal or reniform textures. The opposite, or complementary, relationship is the palmate texture, in which the surface of the grain, as seen in section, is made of a succession of adjacent concave curves separated from each other by triangular or acute protuberances. Dicate is a term that covers the intermediate shapes between mammilate and palmate surfaces, and generally applies to "finger-like" projections.

**MATRIX**
The term is used in sedimentology to indicate the finer synsedimentary material between sand grains. It is used in soil micromorphology to designate the finest material of the soil fabric (S-matrix).

**MONIC**
Stoops & Jongerius (1975) introduced this term for a type of distribution pattern of coarse and fine constituents in which only particles of one size range (or amorphous material) are present. Associated interstitial voids, generally referred to as
packing voids, are invariably present, though they may be ultramicroscopic. This pattern is commonly observed in pure sandy soils and sediments devoid of cementing material.

**M-PLASMA**

This term designates the soil plasma that forms the colloidal part of the surrounding matrix, by opposition to the plasma that may be observed within included pedofeatures. Compare with Plasma.

**OIKOCRYST**

This term designates the large poikilitic crystal that encloses many small crystals of a different mineral. Oikocrysts of an amphibole-group mineral commonly enclose small crystals of plagioclase or pyroxene-group minerals. Compare with oikocryst.

**ORTHIC**

This term, from the Greek root ὀρθός = right, straight, is used in a purely morphological sense and applied to describe the relationships observed in the texture of the pedological feature (concretion or nodule) and that of the adjacent matrix. The term orthic characterizes a concretion whose base material is identical to that of the adjacent matrix; anorthic (same Greek root with the prefix α = without) is used where it is not. The difference between an orthic pedofeature and its matrix lies in the fact that the locally developed concentration of a constituent mineral has obscured the texture of the original matrix, the skeleton grains of which being generally the only constituents still visible. The concentrated constituents may be iron oxides and hydroxides, gibbsite, calcite and other secondary minerals. The distribution and the nature of the skeleton grains; the striated orientation is elongate parallel to each other, or randomly arranged, or the plasma separations may occur in two (bi-) sets of parallel zones, each set being inclined as a definite angle to the other set. This latter fabric is termed biassetic fabric. Where the angle between the two sets is approximately a right angle, the fabric becomes an orthobimasepic fabric.

**PACKING voids**

These are voids due to the random packing of individuals (Brewer 1964). Packing voids are interconnected between them and may be the pathways for absolute accumulations of fine material. All individual voids may exhibit equant size if they are interstitial between skeleton grains of approximately the same size.

**PAPULE**

A papule is a glaebule composed dominantly of clay minerals with a continuous or lamellar fabric; it has a sharp external boundary and is commonly prolate to equant and somewhat rounded.

**PEDOPLASMATION**

Pedoplasmation refers to a near-surface process of formation of secondary minerals, at the expense either of the minerals of the parent rock, or of the previously formed secondary minerals that appeared in subjacent alteromorphs. In this case, the microtextural patterns of the alteromorphs are modified, and part of their secondary minerals is replaced by other secondary minerals of simpler chemical composition, e.g., replacement of smectite-group minerals by kaolinite, or degradation of the pre-existing kaolinite by gibbsite.

**PEDOTURBATION**

All mixings of soil components not caused by illuviation are covered by this term. The process of pedoturbation is a superficial one that tends to destroy the soil textures previously formed by pedological processes. The main factors of pedoturbation are of biological, physical or chemical order, and they act principally in the upper part of
the profiles. They are: the activity of the plant roots, of animals and microfauna of the soil (pedotubules, channels, galleries, etc.), human activity (plowing, work of soil for agricultural or breeding purposes), physical or geomorphological processes (colluvial, creep, and all processes of erosion) and, to a lesser extent, chemical processes that may promote the dissolution of soluble material and consequent crushing, settling and textural re-arrangements of the residual insoluble material.

**PLASMA**

Plasma is used to designate that part of a soil material that is capable of being (or has been) moved, reorganized or concentrated by the processes of soil formation. It is the mobile active part of the soil material. The plasma includes all the material, mineral or organic, of colloidal size and relatively soluble material that is not bound in the skeleton grains. The term may be written as $M$-plasma where it designates specifically the plasma of the soil matrix.

**POIKILITIC**

Where an igneous rock displays a poikilitic texture, small grains of one mineral are irregularly scattered without common orientation in a typically anhedral larger crystal of an other mineral. The included small grains, also called chadacrysts, are commonly pyroxene or plagioclase grains completely embedded in an enclosing large crystal, also called oikocrysts, commonly of amphibole. A poikiloblast (the textural term is poikiloblastic) refers to a large crystal that grew during metamorphism (i.e., in the solid state), also containing numerous inclusions of small grains.

**PORPHYRIC**

This term, introduced by Stoops & Jongerius (1975), refers to a type of related pattern of distribution of coarse and fine constituents in which the coarser particles are completely embedded in a groundmass of finer material; interstitial pores are absent, at least at the scale of the distribution pattern. Depending on the distance between the skeleton grains that are completely embedded in a clayey matrix, one can distinguish a close porphyric related distribution, where many coarse particles have points of contact with each other, and an open porphyric related distribution, where few grains are in contact with each other. Single- and double-spaced porphyric distributions can be distinguished according to the distances between them in relation to their mean diameter.

**PORPHYROSKELETIC**

The term, introduced by Brewer (1964), is equivalent to porphyric of Stoops & Jongerius (1975). The concept is based on the relation of plasma to skeleton grain: the plasma occurs as a dense groundmass in which skeleton grains are set, in a manner recalling phenocrysts in a porphyritic igneous rock.

**QUASICUTAN**

This term refers to a pedological feature that occurs within the S-matrix, not immediately adjoining natural surfaces, but with an obvious relationship to them (Brewer 1964). A quasicutan is a quasicutan whose constituent minerals mainly are oxides and hydroxides of iron.

**SAPROLITE**

Saprolite is a term commonly used by geologists to refer to a typically clay-rich, completely decomposed rock, formed in situ by chemical weathering. The original rock may be igneous, metamorphic or sedimentary, and its original structure is commonly preserved throughout the weathered cover. The thickness of the saprolite may be very thick, principally in humid tropical regions. Saprolite is equivalent to the term alterite, more recently introduced and generally used by soil scientists and other agronomists who study this material in great detail as an intermediate stage in the formation of soil.

**SKELETON**

The term skeleton determines relatively stable residual mineral grains and organisms, the size of which generally corresponds to the sand fraction of the soil. The skeleton grains are generally concentrated or reorganized in specific horizons, associated with colloidal argilplasmas under the influence of pedological processes.

**S-MATRIX**

The S-matrix of a soil material is the material (plasma, skeleton grains, associated voids) within the simplest (primary) peds, or composing pedal soil materials, that do not occur as pedological features other than plasma separations; it may be absent in some soil materials, for example, those that consist entirely of pedological features (Brewer 1964).

**STONE LINE**

A stone line is a continuous or discontinuous line of angular and subangular rock fragments, paralleling a sloping topographic surface and lying just above the parent material of a soil at a depth of a
few meters below that surface. Many old ferralitic soils exhibit stone lines, a few centimeters to one meter thick, generally composed of fragments of quartz, derived from the residual unweatherable quartz veins crossing the parent rock of the soil, and of fragments or gravels of iron duricrusts and other resistant materials. Whether a stone line is autochthonous or allochthonous (in situ concentration of the fragments by settling and sorting by microfauna activity, or allochthonous origin by deposits of gravels on an eroded slope before its burial under more recent colluvial deposits) is generally a matter of discussion. The heterogeneity of the material may in some cases bring arguments for an allochthonous origin of the material of the stone lines. Where the material is homogeneously composed of ubiquitous fragments of quartz, however, the question may not be resolved easily.

**STRESS CUTANS**

The term, proposed by Brewer (1964), refers to an *in situ* modification of the plasma due to differential forces such as shearing. The stress cutans are not true coatings. They develop also between two or more rigid bodies embedded in a soft clayey matrix under the influence of variation of volumes owing to alternations of humidity and dryness; they are then expressed by halos of birefringent oriented clay material contrasting with the unoriented clay-rich matrix. See also *Granosoriated birefringence*. 

**SYMPLECTITIC**

A symplectic texture in an igneous or metamorphic rock is produced by the intimate intergrowth of (usually) two minerals that grew simultaneously. One of the minerals may exhibit a vermicular habit. In this book, the word is used to characterize the intimate assemblage of vermicular grains of magnetite regularly distributed within one (or more) grain of orthopyroxene. This assemblage is interpreted to result from the replacement of an original grain of olivine subjected to thermal metamorphism.

**TOMBOLO**

A tombolo is a bar of sand or gravel or a barrier that connects an island with the mainland or with an other island. Where the island has a relatively large size, two opposite curved (concave) bars may form, isolating a portion of the sea between them and the mainland, leading to a double tombolo.
**Index**

**INDEX OF PHOTOOMICROGRAPHS AND FIGURES**

This Index is arranged in such a manner that the main divisions of the book are easily accessible. The major themes are successively arranged in a natural and logical order of description, from the parent rock to the most intensely weathered bauxitic materials. Each of the fifteen themes listed below is individually indexed. The page numbers cited refer 1) to photographs and their respective captions, or 2) to specific figures, identified in parentheses in bold-face font. The symbols oxFe, oxTi and oxMn represent oxides and oxyhydroxides of Fe, Ti and Mn, respectively.

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About the Author

Jean E. Dehigne, born in Tournai, Belgium, on July 12, 1929, has an academic background in agronomy and the geological sciences. He obtained his doctorate from the Université Catholique de Louvain, in Belgium. He began his professional activities in 1956 at Yangambi, then in the Belgian Congo, where he was affiliated with the Institut National pour l’Étude Agronomique du Congo (INEAC). There, he studied the alteration of the important rocks, mostly basalt, that make up the broad expanses of that country. He also investigated the formation of soil at the expense of volcanic ash emitted by volcanos in the eastern part of the country. His observations relied heavily on optical methods and on the techniques of thermal and chemical analysis available in that setting and at that time.

Forced out of the Congo in 1960 as a result of the tragic events that followed the granting of independence, the author came back to Louvain, where he participated in a synthesis of the field-based results, aided there by X-ray diffraction and electron microscopy. He then joined ORSTOM (Office de la Recherche Scientifique et Technique Outre-Mer) in Paris, and was assigned from 1962 to 1976 to the Adiopodoumé Research Centre, near Abidjan, Côte d’Ivoire. There he founded the Laboratory of Geology, and continued to apply optical methods, techniques of chemical, thermal and sedimentological analysis, and eventually, X-ray diffraction. He became much involved in studies of the alteration of the basic and ultrabasic rocks as well as granites of the Côte d’Ivoire. He focussed on the relations between alteration and geomorphological expression, commonly as iron crusts and bauxite, witnesses of paleoclimatic oscillations that affected this region of western Africa.

After a short time dedicated to the synthesis of his previous findings, spent at the Université de Nice, the author was assigned by ORSTOM to the State University of São Paulo, in Brazil. Up until 1987, he focused his attention on the weathering of basaltic rocks of Riberao Preto (São Paulo) and of the Paraná flood basalt sequence, the nepheline syenites of Poços de Caldas (Minas Gerais), and the carbonatite at Jacupiranga (São Paulo).

Over this long period of professional activity, he rose to the title of Director and “Inspecteur général de Recherches”. He taught courses about the mineralogical response to weathering and the micro-morphology of alterations at the University of Abidjan, the École Nationale Supérieure Agronomique, both in Côte d’Ivoire, and at the universities of São Paulo and Porto Allegre, in Brazil. He was called on to give short courses on the subject for the International Society of Soil Sciences (ISSS), Wageningen, The Netherlands.

Assigned by ORSTOM in 1988 to the Laboratory of Environmental Geosciences at the Université de Marseilles, the author had the opportunity to re-investigate part of his vast collection of thin sections, and to undertake complementary studies of the alteration of rocks. He built up his collection of over 10,000 color slides. He had by then begun preparing the publication of this Atlas. This book represents the culmination of over forty years of professional activity, strongly grounded in field observations, complemented by various types of analyses in the laboratory, but very much focussed on the power of observations made with the optical microscope.
Schematic sketches of the most common alteromorphs
Atlas of Micromorphology of Mineral Alteration and Weathering illustrates lavishly all the steps of weathering from incipient replacement along cracks to complete replacement by secondary minerals. Each of the 610 color photomicrographs from the author’s extensive collection is accompanied by a detailed caption.

In his book, the author, Jean Delvigne, patiently distills the work of a lifetime and successfully bridges the gap between petrological sciences and the soil sciences, with mineralogy as a common thread. He examines the transition between parent rocks and weathered materials that are concealed, and commonly left unsampled, at the base of the soil profile. He deals with problems of classification, description and origin of altered rocks and indurated materials derived from them, and proposes the vocabulary needed to communicate findings in this field. He provides new insight into the diverse paths that high-temperature rocks take to adjust to their new surroundings near the Earth’s surface. In general, weathering reactions are superimposed upon patterns of hypogene alteration.

Here is a textbook and reference manual for a broad spectrum of scientists interested in the weathering and alteration of minerals. This field of study is relevant to soil scientists, agronomists, environmental mineralogists and economic geologists.