

## OLIVINES, THEIR PSEUDOMORPHS AND SECONDARY PRODUCTS

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### Table of contents

1. Introduction
- 1.1. Weathering capability
- 1.2. Importance in soils
2. Unweathered olivine
- 2.1. Mineralogical descriptions
- 2.1.1. Chemical composition
- 2.1.2. Crystallographic data
- 2.1.3. Optical properties
- 2.2. Occurrence
- 2.2.1. In rocks
- 2.2.1.1. Mg-rich olivines
- 2.2.1.2. Fe-rich olivines
- 2.2.2. In sediments
- 2.3. Mineral associations
3. Weathering and alteration products of olivine
- 3.1. Introduction
- 3.2. Pseudomorphs after olivine and secondary products
- 3.2.1. Orthopyroxene
- 3.2.1.1. Occurrence
- 3.2.1.2. Composition and optical characteristics

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no 10.020 (21)

- 3.2.1.3. Micromorphology
- 3.2.2. Serpentine
  - 3.2.2.1. Occurrence
  - 3.2.2.2. Composition and optical characteristics
  - 3.2.2.3. Micromorphology
- 3.2.3. Iddingsite
  - 3.2.3.1. Occurrence
  - 3.2.3.2. Composition
  - 3.2.3.3. Optical characteristics
  - 3.2.3.4. Micromorphology
- 3.2.4. Chlorite and chloritic material
  - 3.2.4.1. Occurrence
  - 3.2.4.2. Composition and optical characteristics
  - 3.2.4.3. Micromorphology
- 3.2.5. Bowlingite - Saponite
  - 3.2.5.1. Occurrence
  - 3.2.5.2. Chemical composition
  - 3.2.5.3. Optical characteristics
  - 3.2.5.4. Micromorphology
- 3.2.6. Chlorophaeite
  - 3.2.6.1. Occurrence
  - 3.2.6.2. Chemical composition
  - 3.2.6.3. Optical characteristics
- 3.2.7. Nontronite and ferriiferous Beidellites
  - 3.2.7.1. Occurrence
  - 3.2.7.2. Chemical composition
  - 3.2.7.3. Optical characteristics
  - 3.2.7.4. Micromorphology
- 3.2.8. Iron hydroxydes and ferruginous amorphous materials
  - 3.2.8.1. Occurrence
  - 3.2.8.2. Chemical composition
  - 3.2.8.3. Micromorphology
- 3.3. Conclusions
  - 3.3.1. Crystal chemistry and mineralogy
  - 3.3.2. Geochemistry
  - 3.3.3. Micromorphology
- 4. Proposals

References

Summary

Résumé

Samenvatting

Photos

## 1. INTRODUCTION

This paper is intended to help the micromorphologist and other earth scientists to recognize olivine and its alteration products in thin sections of soil and weathered rocks. The publication is a follow-up

of the introductory paper by Stoops *et al.* (1979) in which the description of individual weathering minerals with their morphology and degree of weathering were outlined by the Advisory Panel on Weathering and Neof ormations of the Subcommittee on Micromorphology of the International Society of Soil Science (I.S.S.S.).

### 1.1. WEATHERING CAPABILITY

Olivine is considered to be one of the least stable silicate minerals of the igneous rocks : it takes first place in the weathering sequence described by Goldich (1938) and belongs to group 3 of the weathering sequence of clay-sized minerals described by Jackson (1948), and in the stability sequences of Pettijohn (1941), Fieldes & Swindale (1954) it appears at the bottom of the list as the most weatherable component. Olivine has a weathering potential index (W.P.I.) of 44 to 65 i.a. the highest value of the rock forming silicates (Reiche, 1950).

### 1.2. IMPORTANCE IN SOILS

Olivine is one of the important primary minerals of various basic and ultramafic rocks and can for instance be found in volcanic ashes, lavas and cone material. Olivine is frequently a major constituent of basaltic rocks, a rock-type which forms the parent material of many fertile soils due to the abundance of nutrients amassed in it. A second asset is the fact that olivine-containing rocks and associated soils may occur over considerable distances which make these soils important targets for both large and small scale agricultural projects.

In most cases, olivine is destroyed or replaced in the early stage of rock weathering and consequently does not appear, as fresh minerals remnants, during the later stages of soil formation. Nevertheless we can find fresh olivine in the following situations :

- a) In the vicinity of large basic or ultramafic outcrops, fresh or moderately weathered rocks are destroyed by active erosion processes. Under such circumstances, fresh olivine can be maintained in rock fragments and sands which form a part of displaced or *in situ* weathered soil materials.
- b) In soils formed from recent volcanic ashes, olivine can be identified as euhedral fresh crystals associated with augite and hornblende crystals. Ageing of these ashes gives alteration products which vary according to regional drainage conditions, viz. olivine disappears rapidly and is replaced by iron hydroxides under good drainage conditions, while nontronite and other clay minerals replace olivine in poorly drained areas.

c) In older soils, regoliths and weathered rocks, olivine may be found partly transformed into secondary minerals under the influence of post-magmatic processes. These secondary minerals are often more stable under superficial conditions than olivine, e.g. a cortex of iddingsite which surrounds an olivine core, or a reaction rim of pyroxene or garnet around a core. Consequently, the olivine in the core is protected and may remain undisturbed for longer times in soils.

In general thus, fresh olivine will be found only in recent to sub-recent upper formations, in all other cases the mineral is, at least partly, replaced by pseudomorphs or by dispersed hydrated minerals. Due to its instability and restricted geological occurrence, olivine, when present, can be a good indicator of the type of parent material in which a soil formed and the degree of weathering of this material. Even when no more olivine is present, recognition and identification of its alteration products may help to identify the parent material.

## 2. UNWEATHERED OLIVINE

### 2.1. MINERALOGICAL DESCRIPTIONS

#### 2.1.1. Chemical composition

Olivines belong to the nesosilicates and their structures consist of independent ( $\text{SiO}_4$ ) tetrahedra linked together by divalent Fe and Mg atoms in six-fold coordination. Olivines form a complete isomorphic series between *Forsterite* ( $\text{Mg}_2\text{SiO}_4$ ) and *Fayalite* ( $\text{Fe}_2\text{SiO}_4$ ) and have  $(\text{Mg, Fe})_2\text{SiO}_4$  as a generalised formula.

These are : *Forsterite* (Fo<sub>90-100</sub>), *Chrosolite* (Fo<sub>70-90</sub>), *Hyalosiderite* (Fo<sub>50-70</sub>), *Hortonolite* (Fa<sub>70-50</sub>), *Ferrohortonolite* (Fa<sub>90-70</sub>), *Fayalite* (Fa<sub>100-90</sub>).

Silicon is not replaced by aluminium as in chain and sheet silicates. The octahedral positions are almost exclusively occupied by divalent atoms and trivalent Al and Fe atoms are absent or present in only very small quantities. Replacement of  $\text{Mg}^{++}$  and  $\text{Fe}^{++}$  by  $\text{Mn}^{++}$  and  $\text{Ca}^{++}$  may occur in minerals of the olivine group : *Tephroit* ( $\text{Mn}_2\text{SiO}_4$ ), *Knebelite*  $(\text{Fe, Mn})_2\text{SiO}_4$ , *Monticellite* ( $\text{CaMgSiO}_4$ ). Olivine crystals commonly show zonations : a Mg-rich core is usually surrounded by a Fe-rich rim but inversion of the zonation is not excluded.

#### 2.1.2. Crystallographic data

Orthorhombic system : 2/m 2/m 2/m

Cleavages : (010) and (100) imperfect in Fo but (010) moderately developed in Fa.

Habit : in hand specimen : olivine is generally tabular to prismatic - (110) - (210) - (010) crystal faces - terminated by pyramidal (101) - (021) faces. Euhedral crystalline forms are sometimes particularly well developed in volcanic ash deposits.

In thin section : olivines of effusive rocks (basalts) generally have a bipyramidal prismatic form but in plutonic rocks most olivine grains are anhedral with irregular concave limits due to convex forms of adjacent pyroxene grains. Curved cracks, locally filled with opaque minerals, are very frequent in olivine.

### 2.1.3. Optical properties (Tröger 1971)

Optical orientation :  $a = z$ ,  $b = x$ ,  $c = y$ ; the optical plane is parallel to (001).

	Forsterite	Fayalite
$n_x$ or $n_\alpha$	= 1.636	1.827
$n_y$ or $n_\beta$	= 1.651	1.869
$n_z$ or $n_\gamma$	= 1.669	1.879
$\delta$	= 0.033	0.052
$2V_z$	= $84^\circ$	$2V_x = 50^\circ$
Opt.	+	-
Disp.	$r < v$	$r > v$

Colour in thin section : colourless or, very occasionally, pale green (forsterite) to pale yellow and yellowish (fayalite); weak pleochroism from pale yellow ( $x = z$ ) to orange yellow ( $y$ ).

Inclusions : frequently minute microlites of magnetite or chromite parallel to (001) or (100); inclusions of orthopyroxene, magnetite, spinel, amphibole and phlogopite are sometimes observed.

## 2.2. OCCURRENCE

### 2.2.1. In rocks

#### 2.2.1.1. Mg-rich olivines

Forsterite and Mg-rich members of the group are characteristic minerals of ultramafic and basic igneous rocks. Olivine occurs as a main constituent (more than 90 %) in dunite and is an important component of e.g. *peridotites*. It is a minor component of some *gabbros*, *norites*, *kentallenites*, etc. Olivine can occur in volcanic rocks as a main constituent in *picrites* and as a minor component in *olivine-basalts*, *basanites*, *dolerites*, etc. Olivine occurs frequently in

volcanic ash deposits of basaltic or basanitic composition. Forsterite can also be present in metamorphosed dolomitic limestones (*forsterite marbles*) and associated with metallic iron and orthopyroxene in certain *meteorites*.

#### 2.2.1.2. *Fe-rich olivines*

Fayalite and other Fe-rich olivines occur in small quantities in acid and sodic plutonic and volcanic rocks, in certain *quartz-syenites* and sometimes in *special granite varieties*. Fayalite is present in some Fe-rich metamorphic sediments (*eulysite*) and is a characteristic constituent of *furnace slag*.

#### 2.2.2. In sediments

Olivine may occur as a minor detritical constituent of some sediments derived from the rocks mentioned above. However olivine is not maintained for very long in such sediments and in older geological sediments has completely disappeared in most cases. Only in beach sands of volcanic islands, or at the base of cliffs composed of ultramafic rocks, one may find olivine as a principal constituent of sands (*olivine sands*). It can be found as a principal constituent of *volcanic ashes* surrounding volcanoes.

### 2.3. MINERAL ASSOCIATIONS

Olivine is mainly associated with other basic or ultramafic minerals that crystallized during the first stages of magmatic fractionation, viz. with pyroxenes (enstatite, bronzite, hypersthene, augite), with certain amphiboles (hornblende, cummingtonite, tremolite) and with ores (magnetite, titanomagnetite, ilmenite, chromite and Fe-Ni-Cu sulphides). In the melagabbronorites, gabbros, basalts and dolerites, olivine is also associated with calcic plagioclases. In silica-poor rocks, mainly of effusive origin, olivine may be associated with leucite or nepheline. It is very rare in quartz-bearing rocks.

During the later stages of magmatic crystallization or in some metamorphosed basic igneous rocks, olivine reacts with other minerals or with the interstitial liquid to give coronas or reaction rims mainly composed of orthopyroxene (sometimes in symplectic association with magnetite or spinel), diopsidic augite, amphibole, spinel or garnet. Forsterite is commonly found together with biotite or phlogopite.

In the largely metamorphosed and tectonized areas, olivine, mainly in the ophiolitic rock-types, is associated with or completely trans-

formed to serpentine and/or talc (*serpentinites*). In lamprophyres a large variety of alteration products is known, sometimes indicated by the general term *pilite* (Velde, 1968).

### 3. WEATHERING AND ALTERATION PRODUCTS OF OLIVINE

#### 3.1. INTRODUCTION

When studying the weathering of olivine in soils and rocks, it must be kept in mind that this mineral has usually already been altered in the rock by deuteric or hydrothermal processes or by magmatic differentiation as a result of subsequent equilibria :

- Magmatic transformations : olivine into intergrowths of orthopyroxene and magnetite which can eventually transform into hornblende or cummingtonite.
- Metamorphic transformations with hydration processes : olivine into serpentine or talc very often accompanied by minute exsolutions of magnetite.
- Deuteric alteration with cation movements : olivine into iddingsite or into other phyllosilicates.

The physical structure of the olivines is compact and strong but these minerals are composed of independent ( $\text{SiO}_4$ ) tetrahedra linked together by readily soluble divalent ions ( $\text{Mg}^{++}$ ) or oxidizable divalent ions ( $\text{Fe}^{++}$ ). The high ratio of divalent cations to silicon (2:1) readily results in a chemical attack on the outer surfaces of olivine or along its inner fractures, since these cations are largely unprotected by silica tetrahedra at these sites. The ferrous iron rapidly oxidizes to ferric iron and the magnesium tends to coordinate with hydroxyl groups or to go into solution. The immediate weathering product is frequently a mixture of iron oxide and hydrated magnesium silicate. This alteration product belongs to the family of smectites or montmorillonites if silica and magnesium are partly maintained, or it forms a mixture of iron oxide or hydroxide with opal when magnesium is removed. A mixture of goethite and haematite in various stages of crystallization may form if both magnesium and silica are removed. Because of this surface reactivity olivine minerals tend to disappear rapidly under acidic weathering conditions. Consequently, fresh olivines are virtually non-existent in well-oxidized soil horizons.

It is frequently difficult to prove whether an alteration product of olivine is due to superficial or to deep seated processes. This is particularly the case with secondary minerals like iddingsite and chlorite, the formation of which takes place at relatively low temper-

atures. It is possible that this also applies to other minerals such as serpentine and talc.

### 3.2. PSEUDOMORPHS AFTER OLIVINE AND SECONDARY PRODUCTS

In the following descriptions most secondary minerals which replace olivine - whatever their origin - are included.

#### 3.2.1. Orthopyroxene

Olivine minerals are very often completely or partially transformed into pyroxene (sometimes into amphiboles) under the influence of late-magmatic processes. If such a transformation is complete and the olivine has entirely disappeared, then it does not concern our study because such a pyroxene itself constitutes a "primary" mineral which in turn will alter to specific secondary minerals. However, the transformation of olivine is very often far from complete and both pyroxene rims and remnants of the original mineral will follow individual transformation sequences.

Nevertheless, these transformations are interesting for the soil scientist for at least two reasons :

- Pyroxene coronas which surround the olivine cores, if complete, may act as a protecting rim. Therefore, these olivines may be observed, if not fragmented, nearer to the soil surface than ordinary unprotected olivine.
- The orthopyroxene rim frequently presents a particular structure of symplectic intergrowth with opaque minerals. This structure is very characteristic and can be maintained in an undisturbed form for longer periods in weathered rocks and soils. It is a valuable aid in identifying secondary products of both orthopyroxenes and olivines even when both minerals are completely weathered.

##### 3.2.1.1. Occurrence

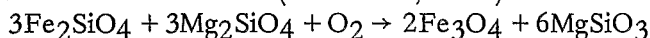
Orthopyroxenes (enstatite, bronzite, hypersthene) are common as late magmatic transformation products of olivine in coarse to medium-grained igneous rocks such as pyroxenites or peridotites. The transformation occurs less frequently in fine-grained effusive rocks.

##### 3.2.1.2. Composition and optical characteristics

The reaction between olivine crystals and the residual liquid from which they precipitated is discontinuous. This is recorded as partly resorbed olivine crystals and reaction rims of peripheral orthopyroxene



which can be associated with vermicular intergrowths of magnetite (symplectic structure). The reaction may be due to an oxidizing process due to the reaction (Muir et al., 1957) :



With this theoretical formula it is clearly demonstrated that both the proportions and compositions of the end products will depend on the initial composition of olivine minerals. In other words, in forsterite and Mg-rich olivines, the quantities of newly formed magnetite are very small and the composition of the orthopyroxene is nearest to that of enstatite or bronzite, whereas with more ferruginous olivines, the magnetite component will become more abundant and/or the orthopyroxene composition could approach that of hypersthene. Accurate chemical and optical analyses (Ramberg & De Vore, 1951) have shown that olivine contains less Mg than the pyroxene with which it is associated when the average molecular fraction  $(X_o + X_p)/2$  is less than about 0.65.

The Mg-rich orthopyroxenes which develop from olivine are readily distinguished by their straight extinction, lower birefringence (interference colours from grey to yellow or orange) and pleochroism in the case of bronzite and hypersthene (pale green to pink or reddish).

### 3.2.1.3. *Micromorphology*

Orthopyroxene rims around olivine cores are formed inside the original limits of olivine grains and the external outline of orthopyroxene very often follows the original olivine outlines. Conversely however either the external outline is larger than the original olivine limits, or invasion of some of the neighbouring minerals occurs under the influence of metamorphic processes or when coronas or reaction rims are formed with other minerals such as plagioclases.

The orthopyroxene rim is very often irregular and incomplete and may be composed of pure bronzite, hypersthene or orthopyroxene in symplectic association with irregular and lamellar intergrowth of magnetite (see fig. 1 and photo 1). The inner limit which is in contact with the olivine core, is also irregular and does not follow any crystallographic orientation of the replaced mineral. The inner fractures, often observed in fresh olivine, may totally disappear in the newly formed pyroxene.

Olivine cores may be completely replaced by iron hydroxides or by smectitic material in slightly weathered rocks, whereas the pyroxene component remains entirely fresh. In moderately weathered rocks, both olivine cores and orthopyroxene rims are weathered into very

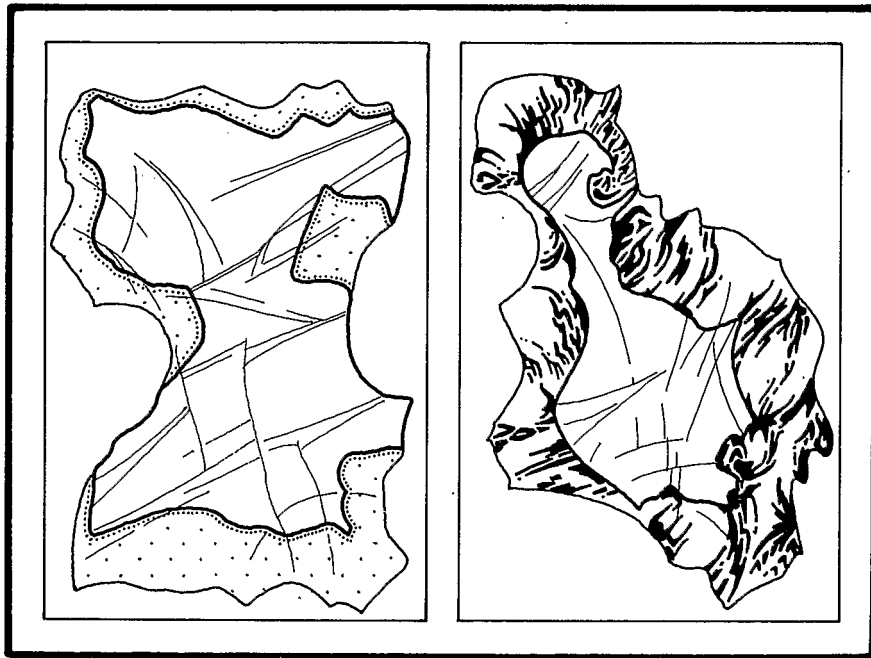


Fig. 1

Olivine alteration into orthopyroxenes

- a. Into bronzite : incomplete and irregular rim of orthopyroxene (dotted) around unaltered core of olivine. Inner cracks in olivine are sometimes continuous in the outer rim of the bronzite.
- b. Into hypersthene + magnetite : complete but irregular cortex with a symplectic structure composed of an intergrowth of orthopyroxene and magnetite lamellae. This specific but frequently occurring association is very useful for the recognition of the weathering products after olivine even if both olivine and orthopyroxene are completely weathered, because the symplectic structure is very stable and usually undisturbed during weathering.

similar substances, but the presence of untransformed symplectic magnetite permits the original limits of both primary minerals to be distinguished easily. The grain size of the secondary products is often somewhat different for olivine and orthopyroxene. When both minerals are transformed to iron hydroxides, the observed structure is irregular cellular (no cleavages but curved fractures) in olivine and is regular cellular (good (210) cleavages) in orthopyroxene. When both minerals are weathered to nontronite, differences between them become less clearly visible, although sometimes the flakes of the smectite component are a little more elongated and oriented in olivine than in pseudomorphs after pyroxene. In completely weathered rocks

magnetite of the symplectic structure has also disappeared and is transformed into haematite pseudomorph after magnetite in oxidized weathered rocks. The magnetite can also give some brownish to reddish colours to the embedding nontronite whereas the nontronite weathered from olivine retains its greenish colours.

Under the influence of late-metamorphism, olivine may be transformed into serpentine, chlorite or iddingsite whereas orthopyroxene may remain untransformed or be converted to talc, cummingtonite or tremolite.

### 3.2.2. Serpentine

#### 3.2.2.1. Occurrence

Secondary minerals which belong to the serpentine group are often observed as pseudomorphs after olivine in ophiolitic rocks and ultramafic intrusions. The serpentinization is particularly well developed in olivine-rich rocks such as dunites and some peridotites.

In entirely serpentinized rocks, serpentine minerals appear under the influence of late or post-magmatic processes associated with tectonism and regional or general metamorphism. Generally, serpentine minerals cross the olivines as a banded network in which the fibrous units of serpentine are disposed perpendicularly to the central plane of each band. This pattern is emphasized by minute magnetite deposits. In rocks with a high olivine content the banded pattern is composed of a transmineral linear and crossed fracture network. In rocks with a lower olivine content e.g. pyroxenites and gabbros, serpentine minerals are only found in olivines along the transmineral fractures whereas the other original minerals are transformed into talc, actinolite and other similar hydrated secondary products along these fractures.

In some cases, transformation of olivine into serpentine is accompanied by a simultaneous transformation of orthopyroxene into bastite or talc and of clinopyroxene into actinolite, tremolite or other uralitic minerals.

When in contact with acid pegmatitic veins, serpentine minerals may be associated with recently crystallized apatite grains. Serpentinization is followed by quartz deposits in other cases.

In serpentinized olivine-poor rocks such as olivine bearing pyroxenites, a radial network of open or filled fractures is often observed which radiate from the serpentinized pseudomorphs into and through adjacent minerals. These radiating fractures are caused by volume changes during transformation of the original olivine into serpentine.

### 3.2.2.2. Composition and optical characteristics

The general formula of the serpentine minerals is  $Mg_3Si_2O_5(OH)_4$ . These are trioctahedral phyllosilicates. They do not contain aluminium and the iron previously contained in the oliviness is not admitted into the crystal lattice of these sheet-silicates and usually crystallizes into minute magnetite aggregates.

The serpentine group is composed of three distinct species : chrysotile, lizardite and antigorite. All these minerals belong to the monoclinic system and are colourless to pale green in thin section. The refractive indices are somewhat higher in antigorite than in chrysotile (Tröger 1971).

	Chrysotile	Lizardite	Antigorite
$n_x$ or $n_\alpha$	1.532–1.552	1.538–1.550	1.546–1.595
$n_z$ or $n_\gamma$	1.545–1.561	1.546–1.560	1.552–1.604

It is always difficult, in thin section, to distinguish between the three varieties of serpentine minerals. A clear distinction is possible with X-ray diffraction and especially with electron microscopy. Because of the similar chemical composition of the three minerals, an accurate identification is not always necessary for geochemical or pedological purposes.

The transformation of olivine into serpentine may be partial. Olivine cores remain fresh or may be transformed during a later process, into a new mineral phase, such as iddingsite, without destroying the previously formed serpentine.

In some cases serpentine may resemble chlorite but serpentine generally has a lower birefringence, is very often colourless and exhibits no pleochroism in thin section.

### 3.2.2.3. Micromorphology

The micromorphological aspects of serpentized rocks varies and is related to the initial quantity of olivine - or orthopyroxene which can also transform into serpentine - present in the rock.

— *In olivine-rich rocks* such as dunites and peridotites, serpentinization may or may not be complete. If the transformation is incomplete we can observe a serpentine mesh structure composed of a lattice work of longitudinally divided cross-fibre veins enclosing olivine cores. Each olivine grain may be divided into several cores which retain their original orientation without disturbance. Generally, the serpentine veins contain two parallel series of fibrous material separated by a black band of minute magnetite

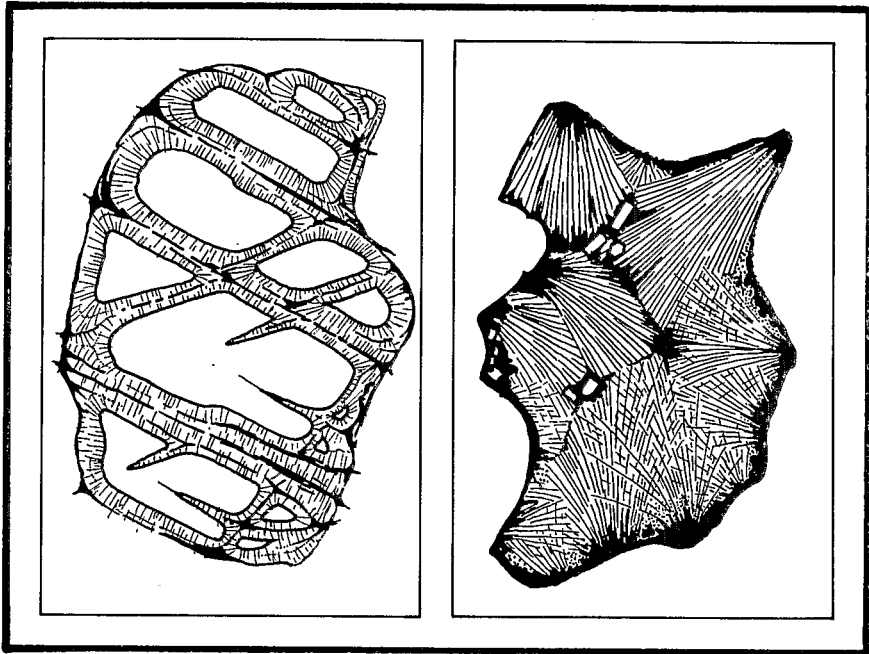


Fig. 2

Olivine alteration into serpentine

- a. Into antigorite : an irregular banded structure follows several inter-, intra-, and trans-mineral fractures in a coarse-grained dunite. Bands of secondary minerals are composed of two parallel serpentine layers separated by an irregular deposit of magnetite; the iron content of the original olivine is not admitted into the serpentine lattice, and forms secondary magnetite.
- b. Isolated olivine grain in a pyroxenite which is completely transformed into a mixture of serpentine (probably chrysotile) with a radiating structure and minute magnetite particles. The magnetite is mainly concentrated near the original grain limits of the olivine and between the radiating units of serpentine. Several apatite crystals can be observed associated with magnetite deposits.

aggregates (see fig. 2a). If the rock is slightly weathered, magnetite may be partially altered into iron hydroxides which change the general colour of the adjacent serpentine to yellowish-brown due to iron migration between the serpentine fibres. The serpentine veins may be solely intramineral but the original grains are often surrounded by intermineral serpentine veins and some of these may even continue throughout several minerals as transmineral veins. If the transformation is complete, the inner parts of the mesh structure are filled by serpentine microaggregates. These may appear as nearly isotropic or as microcrystalline with a watered appearance.

– *In olivine-poor rocks* such as pyroxenites or gabbros, wall-minerals adjacent to rock fractures are often transformed. Olivine is altered into serpentine whereas other primary minerals are partially or completely transformed into other secondary minerals such as talc inside orthopyroxenes, actinolite inside clinopyroxenes and chlorite inside amphiboles. The structure of serpentine is often fibro-radiated in completely transformed olivines. A dark rim around the serpentine or irregular patches in it frequently consist of magnetite aggregates, the volume of which seems to be equivalent to that of the original iron content of the unaltered olivine (see fig. 2b). If the transformation agents have a more complex composition, serpentine can be associated with other secondary products such as calcite or magnesite (CO<sub>2</sub>), apatite (P, F, Cl), or pyrite (S). Olivine cores eventually embedded between serpentine veins can, during a later transformation stage, change into iddingsite or chlorite without disturbing the serpentinized structures. Serpentine itself may be transformed into montmorillonite (Wildman, 1967; Wildman *et al.*, 1971).

### 3.2.3. Iddingsite

#### 3.2.3.1. Occurrence

Iddingsite is one of the secondary minerals after olivine which has been the subject of numerous descriptions and analyses. However, authors differ in their opinions concerning the origin of iddingsite. This is possibly due to its similarity with other ferruginous secondary products having the same colour or habit. The latter have a different chemical composition and, consequently, a different mode of origin, deuteric or meteoric. The uncertainty can also be emphasized by superimposing both types of processes e.g. fresh cores of partially iddingsitized olivines may weather to ferruginous products which are difficult to distinguish from iddingsite without accurate observations and analyses.

Iddingsite is generally found as an exclusive alteration product pseudomorph after olivine in basic volcanic and sometimes in ultramafic coarse to medium grained plutonic rocks. It is never found as pseudomorphs after other primary minerals such as pyroxenes or amphiboles and never occurs as filling material in pores and cracks.

Iddingsite may be found as pseudomorphs after olivine together with other secondary products such as serpentine or clayey minerals. Such transformations are the result of two or more successive alteration processes each of which effects part of the original olivine mineral.

During the preliminary transformation phase an olivine grain can be partially transformed into serpentine along its cracks. This leaves fresh olivine cores embedded in serpentine. During a later transformation phase, the olivine cores may be transformed into iddingsite without changing the previously formed serpentine. Iddingsite can be present in rocks in which other minerals (pyroxenes and plagioclases) are perfectly fresh and unweathered.

### 3.2.3.2. Composition

Iddingsite is very variable in composition because it never consists of a single phase and represents a mixture of cryptocrystalline goethite (and possibly haematite) with a phyllosilicate (smectite, chlorite, talc (rarely), micas). Amorphous components may also be present (Sun, 1957; Wilshire, 1958). Although iddingsite is a mixture of two or more phases it sometimes optically behaves as a homogeneous material; its optical homogeneity is due to orientation, in the iddingsite, of the goethite component and of the layer lattice silicates which can be completely or partially inherited from the oxygen framework in the original olivine crystal (Brown & Stephen, 1959).

Table 1  
Chemical composition of some Iddingsites

	after Delvigne, 1979 +			after Wilshire, 1958 ++	
	Olv	Idd	Range Idd.	Idd.	Range Idd.
SiO <sub>2</sub>	36.8	28.3	22.3 - 39.4	41.20	22.08 - 48.36
TiO <sub>2</sub>	-	-	-	0.14	0.12 - 0.26
Al <sub>2</sub> O <sub>3</sub>	-	-	-	3.81	0.00 - 5.09
Fe <sub>2</sub> O <sub>3</sub>	-	43.3	34.8 - 50.2	35.42	25.48 - 60.13
FeO	24.4	-	-	0.38	0.00 - 1.97
MnO	0.3	0.0	0.0 - 0.1	0.05	0.00 - 0.11
MgO	38.6	6.6	4.4 - 8.6	6.85	0.60 - 12.71
CaO	0.0	0.5	0.0 - 0.8	2.35	1.72 - 3.26
Na <sub>2</sub> O	-	0.1	0.0 - 0.2	0.12	0.12 - 0.13
K <sub>2</sub> O	-	0.1	0.0 - 0.2	0.10	0.09 - 0.10
H <sub>2</sub> O <sup>+</sup>	-	21.1	19.0 - 23.3	9.30	5.74 - 11.00
Total	100.1	100.0		99.72	

+ : Analyses made with the electron microprobe of "Laboratoire de Pétrographie de l'Université Catholique de Louvain, Belgique".

++: In : Deer *et al.* 1967.

Alteration of olivine into iddingsite is complex and requires an addition of  $\text{Fe}^{+++}$  ions (Lemaitre *et al.*, 1966). Magnesium is frequently partially removed and the Fe : Mg ratio of iddingsite is high (8:1) compared with the lower ratio (1:2) in the unaltered olivine. The water content of iddingsite is high and of external origin. It is fixed by smectite and goethite minerals. Chemical analyses given in table 1, of some iddingsites from ultramafic rocks from the Ivory Coast (sampled and analysed by Delvigne, 1979) and from rocks in other areas (Wilshire, 1958, in Deer *et al.*, 1967) show that the composition of iddingsite is very variable. The smectite component can be relatively abundant in some samples and almost absent in others. Chemical analyses of a single iddingsite grain, using the electron microprobe, indicate that the silicon and magnesium contents are variable and irregularly distributed. One explanation could be that the distribution of the smectite component - proportional to the measured Mg and Si contents - in the iddingsite is independent from that of the goethite component which may be homogeneously distributed throughout the iddingsite grain. Point analyses with SEM-EDXRA (Bisdorn *et al.*, 1975) confirmed that during the transformation of olivine to iddingsite most of the magnesium and part of the silicon were removed, whereas the iron content increased (see fig. 3, measured by Bisdorn in 1979, on iddingsite and olivine containing samples from the Galapagos Islands (De Paepe & Stoops, 1969)). The problem of the origin and chemical composition of iddingsite has been studied by numerous mineralogists and geologists e.g. Ross & Shannon, 1926; Gay & Lemaitre, 1961; Baker & Haggerty, 1967.

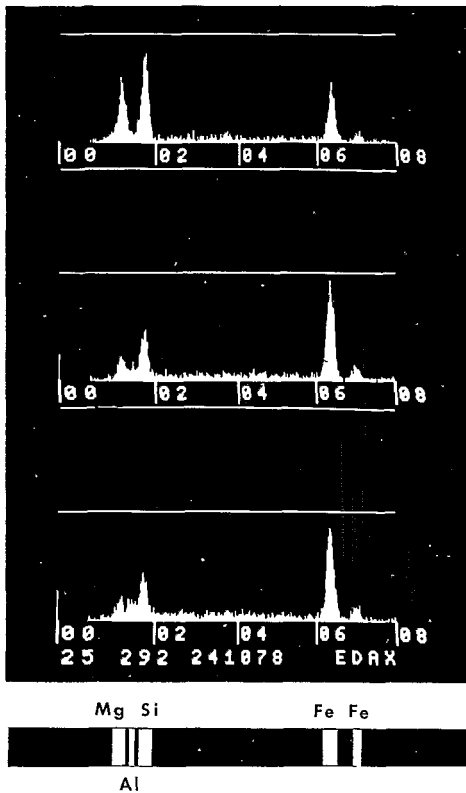
### 3.2.3.3. Optical characteristics

Iddingsite exhibits a morphological and optical homogeneity which results from the fact that the cryptocrystalline newly formed minerals are oriented according to the original structure inherited from olivine: viz. the goethite inherits the oxygen framework of the original olivine completely while this is only partly the case with the layer-lattice silicate components. The (001) direction of the iddingsite exhibits a micaceous cleavage and is parallel to the (100) direction of the olivine (Brown & Stephen, 1959).

The colour of iddingsite in thin section is generally yellowish-brown, sometimes reddish-brown or red, with a weak pleochroism. The refractive index depends upon the degree of iddingsitization and ranges from 1.65 to 1.88 in the most altered varieties and appears to be a function of the goethite content. It seems that the red varieties



SEM-EDAX point analyses of fresh olivine (1) and secondary iddingsite (2-3) in a basaltic rock from the Galapagos Islands (measured by BISDOM, 1979).



1. The fresh olivine core exhibits Mg, Si and Fe.

2. During the first step of iddingsite development, the Mg and Si contents have decreased and Fe has increased. A small peak of Al appears between Mg and Si peaks.

3. In the outer rim of iddingsite, Mg, Si and Fe are virtually unchanged, compared to analysis 2 but Al has increased.

For Mg, Al and Si, only  $K\alpha$  peaks are visible whereas for Fe both  $K\alpha$  (left) and  $K\beta$  (right) peaks can be seen.

Fig. 3

Olivine alteration into iddingsite.

of iddingsite which are principally found in tropical regions, were probably formed by superficial weathering of the iddingsite. These varieties contain haematite which partly replaces goethite and give a change of colour from yellow to red.

The extinction of iddingsite is parallel and  $2V$  varies between 0 and  $90^\circ$ , usually about  $40^\circ$ ; the dispersion is clearly  $r < v$ ; the birefringence is comparable to that of biotite.

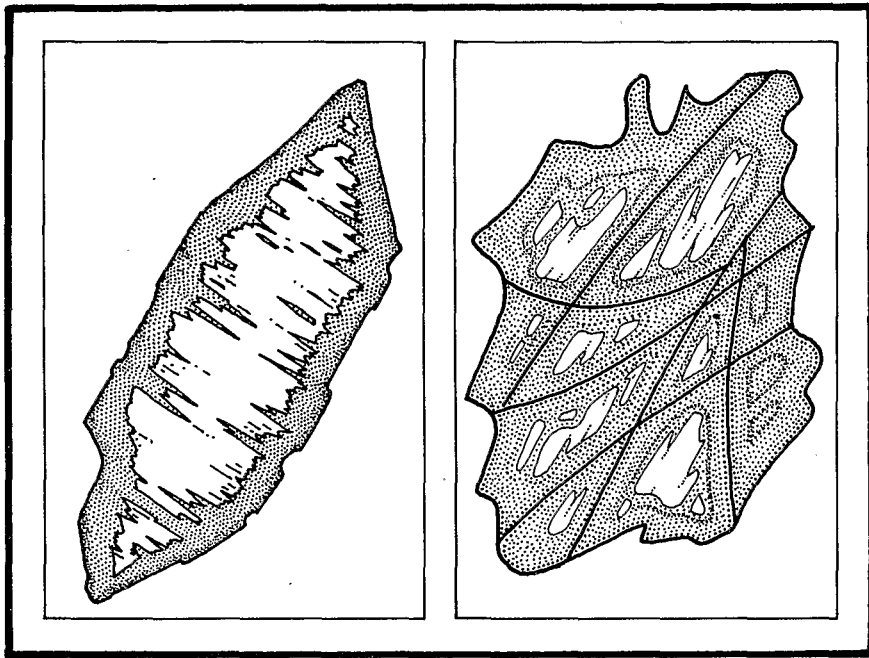


Fig. 4

Olivine alteration into iddingsite.

- a. Regular cortex of brown iddingsite on euhedral olivine crystal in a basaltic rock. The external outline of the iddingsite is regular and follows the original crystal limits. On the inside, however, the contour line of the olivine core is irregular and denticulated : the iddingsite penetration into the olivine core follows crystallographic planes of the host mineral.
- b. Irregular iddingsite pattern. In a coarse grained pyroxenite it originated centripetally from the outer limits of the anhedral olivine mineral and from the network of internal fractures. Olivine cores are irregularly denticulated and most of them are oriented parallel to the c-axis of the original mineral. A concentric zonation is visible in the iddingsite rims which seems to be due to an irregular alteration progress.

#### 3.2.3.4. Micromorphology

Iddingsite occurs in two different morphologies (fig. 4) :

- In basalts and other rocks of volcanic origin iddingsite is yellowish-brown or ochreous-brown and distributed in the outer rim of euhedral olivine grains. This transformation is centripetal and starts with a pellicular stage in which only the outer rim of the olivine is transformed to iddingsite and a last stage in which the olivine core is also completely pseudomorphosed. The transformation is isovolumetric and generally perfect, whereby the outer limits of

the secondary iddingsite follow the outlines of the original crystal. Iddingsite may be distorted parallel to the flow banding in fluidal lavas, proving a partial transformation prior to the solidification of the lava. A second rim of crystallized olivine may be observed locally around a first rim of iddingsitized olivine (Sheppard, 1962). Such an example gives rise to the idea that iddingsitization is of deuteritic origin (Edwards, 1938), when the transitory period of hydrative-oxidative alteration is followed by a renewed period of olivine crystallization.

The inner contact between the olivine core and the iddingsitized rim is less regular because the core is partly denticulated when iddingsite passes into it along a number of crystallographic directions.

- *In plutonic rocks* one can observe a somewhat different transformation. The olivine alteration is always directed centripetally and proceeds along cracks. This produces - before the transformation is complete - several internal cores of unaltered olivine embedded in an irregular boxwork or an irregular cellular mass of coloured iddingsite. It has often been observed, in the iddingsitized parts of the largest olivine grains, that the brown or yellowish colours exhibit zonation. This indicates traces of a successive diminution of the olivine cores during the iddingsitization process.

Drying of samples during thin section preparation produces elongated pores in the iddingsite mass. These pores are parallel to the micaceous cleavage of the iddingsite. In varieties where the smectite component is only present in small quantities and where the iron component is dominant one finds internal inner cracks which are irregular and randomly distributed. A combination of radially and concentrically arranged cracks is sometimes also possible.

It is often very difficult to distinguish between the two varieties of brown alteration products of olivine with only optical studies, as the main optical characteristics are determined by the goethite (or haematite) component, which is responsible for the colour of the iddingsite and also partly responsible for its homogeneous extinction. Additional detailed analyses are necessary in order to distinguish clearly between the two varieties of secondary products. Uncertainty or wrong identification are rather frequent in soils or regoliths in warm tropical regions where superficial weathering can be superimposed on the deuteritic alteration. This superimposing of the two processes can lead to chemical and mineralogical changes without affecting, at first

sight, optical criteria of identification.

### 3.2.4. Chlorite and chloritic material

#### 3.2.4.1. Occurrence

Chlorites are frequently observed along edges or cracks of fresh olivine in slightly deuteric or late magmatic altered rocks. In some cases however, it is not impossible for chlorite to have formed under superficial meteoric conditions. Chlorite formation at the expense of olivine is especially found in magnesium-rich intrusive basic or ultramafic rocks where olivines have a composition nearest to that of forsterite. Secondary chlorite is frequently impure and consists of a mixture of chlorite and interstratified smectite-chlorite clay minerals.

#### 3.2.4.2. Composition and optical characteristics

The chemical composition of the secondary chloritic minerals is very variable and depends upon the original type of transformation. In most cases, chloritic material is formed by the addition of some aluminium, possibly potassium and variable amounts of water to the chemical elements present in olivine. Some magnesium removal is often observed. External ion transfer is necessary for the transformation of olivine into chlorite whether this occurs superficially or deeper in the earth's crust.

The colours of the chlorite-like materials vary from yellowish-green to deep green and from orange to brown or red. The degree of iron oxidation and iron segregation into minute particles which act as a pigment, are probably responsible for these colour changes. The red varieties of chlorite-like materials can be difficult to distinguish from iddingsite in completely altered olivines.

The green chloritic material usually has a birefringence of about 0.006, is biaxial with a low 2V and is often optically negative. The smectitic components may be rather strongly pleochroic in shades of green or sometimes from green to colourless. They have a high birefringence (0.026 to 0.031), a low 2V, are optically negative and have a straight extinction.

Accurate X-ray analyses have demonstrated that in some cases the newly formed material after olivine was composed of swelling-chlorites (Dausse & Brousse, 1966), interstratified chlorite-montmorillonite minerals (Earley & Milne, 1955), irregularly interstratified chlorite-saponite phyllosilicate (Veniale, 1962), and a regular talc-saponite mixed-layer mineral (Veniale & Van Der Marel, 1968).

### 3.2.4.3. *Micromorphology*

Chlorite material principally develops along irregular cracks which are often arranged more or less perpendicular to the c-axis of the olivine. Like iddingsite, the transformation of olivine into chlorite may occur along internal fractures but the micromorphological aspect is quite different.

At first a fine "sawtooth pattern" of secondary chlorite forms along cracks and at a later stage large "teeth" of this newly formed mineral are projected into the remaining fresh olivine. All apices of these "teeth" are oriented according to the c-axis of the original olivine whatever the orientation of the original fractures. The "teeth" are more or less symmetrically disposed at the beginning of the alteration process and on both sides of the fracture. They have a pattern resembling a rosary with irregular diamond-shaped surfaces that protrude into the original olivine crystal. The flakes are randomly distributed within the secondary green chlorite material and do not follow a specific direction such as the crystallographic axes of the olivine or the previous crack patterns. Isolated olivine remnants embedded inside the green material composed of chlorites retain the optical continuity of the original olivine crystal. Very often and at the end of such a transformation process, the green or yellowish-green colour of chlorite changes to a more brownish colour. This change which may possibly occur under the influence of weathering, is interpreted as the result of the release of iron from phyllosilicate, in the form of minute particles of iron hydroxide. These are disseminated between the flakes and produce an irregular limonitic staining in the entirely transformed pseudomorphs (see fig. 5).

The mineralogy and micromorphology of green smectitic and chloritic pseudomorphs after olivine - including iddingsite - have been particularly well studied by Baker & Haggerty (1967).

### 3.2.5. *Bowlingite - Saponite*

#### 3.2.5.1. *Occurrence*

Bowlingite is a green substance of a microcrystalline or lamellar nature. It is an alteration product, pseudomorph after olivine but also after other minerals. Some cases of bowlingite pseudomorphs after pyroxene or other ferro-magnesian minerals have been recorded.

#### 3.2.5.2. *Chemical composition*

Bowlingite, like iddingsite, is very variable in composition. Neither

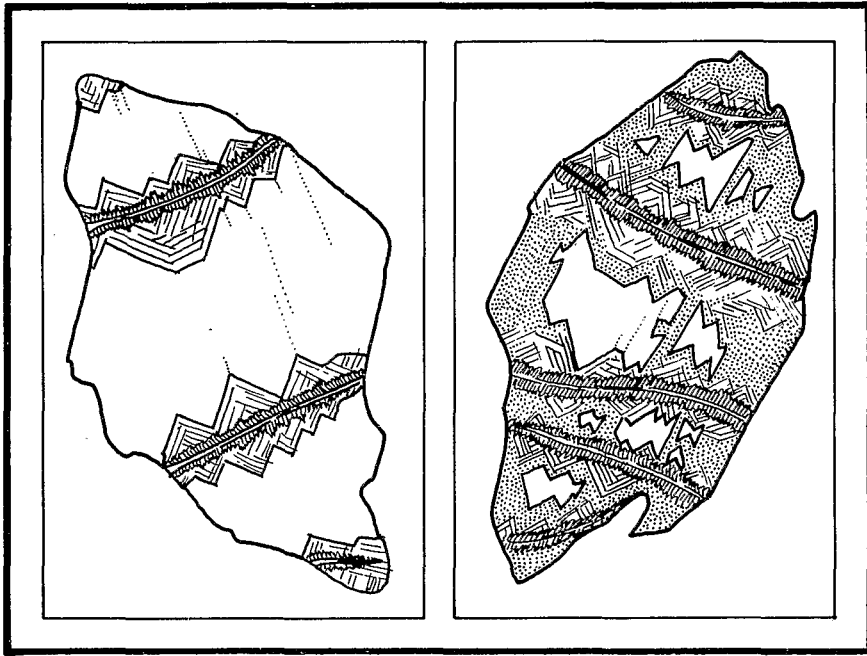


Fig. 5

Olivine alteration into chlorites.

- a. Partially transformed almost euhedral olivine in a basaltic rock. During the first step of transformation short flakes of green chlorite are perpendicular to the fracture-surface and protrude into the primary olivine (close hatched). These chlorite flakes have a low birefringence. During a second phase the transformation products of olivine follow a saw-tooth pattern. This area consists of micaceous flakes (hatched) composed of an interstratified clay mineral with a chlorite-smectite composition. They have a much higher birefringence than the chlorite of the first phase.
- b. Almost completely transformed olivine in the same weathering profile as (a) : During a third phase olivine remnants are transformed to a pure, yellowish-green smectite (frequently called "bowlingite") which crystallizes as a very fine-grained material. This third phase of transformation is probably the result of a weathering process acting on olivine already partially transformed by deuteric processes.

consists of a single phase but comprises a mixture of more than one mineral. Chemical investigations (Hannay, 1877; Wilshire, 1958) on green bowlingite have shown that it is a mixture of smectite-chlorite and serpentine minerals, with minor amounts of talc, quartz and micas. Some samples have a composition close to that of pure smectite and in such cases the mineral bowlingite has been re-named saponite (Caillère, 1935; Caillère and Henin, 1951). Saponite is a trioctahedral

smectitic clay-mineral, the octahedral layer of which is occupied by Mg cations (Grim, 1953). This mineral is mainly formed after forsterite and Mg-rich olivines but is also dependent on the leaching intensity in the level of alteration. If Mg is removed the Fe of olivine oxidizes and accumulates. This leads to the formation of smectites with a chemical composition closest to that of nontronite, a dioctahedral smectite in which  $\text{Fe}^{3+}$  cations replace  $\text{Mg}^{2+}$  in the octahedral layers. Saponite, like nontronite, contains some  $\text{Al}^{3+}$  which replaces  $\text{Si}^{4+}$  in the tetrahedral layer. This Al-content may be very small but it raises the problem as to why aluminium is present in a pseudomorph formed after a mineral which originally contained no aluminium. It is very likely that the Al-content of these clays is due to deuteritic or weathering processes which allow some aluminium transfer from adjacent minerals. We have, in a previous chapter already seen that iddingsite may also contain some aluminium.

The composition and colour of these complex minerals can sometimes be compared to the crystallized material filling amygdalae and joints, particularly in shallow basic intrusions (Hayashi *et al.*, 1961).

### 3.2.5.3. Optical characteristics

Bowlingite appears to be a micaceous fine-grained aggregate in which the individual flakes are usually randomly distributed. The flakes have a yellow, green and brown pleochroism and a refractive index between 1.48 and 1.62. The colour of bowlingite depends on the impurities present, the degree of oxidation of its Fe-constituents and on the percentages of saponite or nontronite present in the pseudomorph. The bowlingite mainly derived from Mg-rich olivine is less coloured than the chloritic or nontronitic varieties formed from Fe-rich olivines or which are present in amygdalae, joints and cracks of the rocks.

The extinction of the pseudomorph is not homogeneous due to the random distribution of the fine aggregates. In special cases, however, when formed from olivine or other ferro-magnesian minerals, preferential orientation can sometimes be observed as a maximum extinction position parallel to the crystallographic axis of the host mineral. In this case, the secondary clay flakes are larger and resemble mica flakes.

### 3.2.5.4. Micromorphology

The transformation of olivine into bowlingite or saponite is also centripetal, as in the case of iddingsite, but has a more irregular

pattern. Transformation generally starts along internal fractures or in the inner part of the olivine cores. This gives patches of green smectite mixed with irregular olivine remnants. This transformation is often relatively fast and complete. Consequently, it is often difficult to find olivine grains which are in an intermediate stage of alteration.

Clayey flakes are often radially disposed in the partially altered grains. The outer limits of the radial aggregate represent either the original olivine limits or intramineral fractures, whereby a single olivine crystal is transformed into several radiating groups of flakes.

Crystallization may be regular or irregular; it would seem that the Mg-smectites tend to crystallize into larger flakes than the Fe-ones. The outer part of the radiating arrangement, in contact with the grain limits, is frequently formed by minute and disordered flakes randomly oriented. The central part of the aggregate however, shows a regularly radiating pattern of larger smectite flakes. The different sheafs of flakes are often separated by fine cracks due to the swelling and shrinkage of the smectite component. These cracks are sometimes filled by either iron hydroxides or minute secondary smectite crystallites.

Without the help of chemical and X-ray analyses, it may be difficult to distinguish between Mg-smectite (saponite) and Fe-smectite (nontronite). Under the microscope nontronite is generally more coloured - shades of green - and tends to crystallize into smaller particles than saponite. When in doubt, the term "green smectite" is preferred to avoid using any ambiguous mineralogical terms (see "proposals").

### 3.2.6. Chlorophaeite

#### 3.2.6.1. Occurrence

Chlorophaeite is also a pseudomorph after olivine but it is sometimes recorded as an alteration product of volcanic glass present in basaltic and other volcanic rocks (Rao, 1942; Sarbadhikari *et al.*, 1966; Stokes, 1968).

#### 3.2.6.2. Chemical composition

Chlorophaeite is probably a mixture of two or more phases viz. goethite with chlorite or goethite with amorphous material but calcite has also been mentioned in the literature. Chemical analyses (Peacock & Fuller, 1928; Wilshire, 1958) show that, in comparison to the original composition of olivine, magnesium was partly removed, iron was partly oxidized to give a mixture of ferrous and ferric cations, and silica, was largely increased in some samples. Peacock & Fuller give



a general formula for chlorophaeite :



As was the case in some previously described secondary minerals of olivine, small quantities of aluminium seem to have been added to the original chemical composition of olivine.

### 3.2.6.3. *Optical characteristics*

Chlorophaeite occurs as a cryptocrystalline or isotropic bright orange to deep green coloured substance with a refractive index between 1.50 and 1.62. The chemical composition of this mineral is very variable and an accurate identification is not always possible. Therefore it would seem preferable, as was the case with bowlingite, to use a general term for chlorophaeitic material, e.g. "orange isotropic material" or "green cryptocrystalline substance" (see "proposals"). Chlorophaeite and palagonite are sometimes confused under the microscope (Peacock, M., 1930, Raw, 1943). However, these two minerals have a different composition (more aluminium in palagonite), occurrence (palagonite mainly occurs in partly vitreous lavas), appearance (palagonite is mostly isotropic) and mode of origin (chlorophaeite is mainly a pseudomorph after ferro-magnesian minerals whereas palagonite is a hydration product of clear basaltic glass at low or moderate temperatures).

### 3.2.7. Nontronite and ferriferous Beidellites

#### 3.2.7.1. *Occurrence*

Nontronite and  $\text{Fe}^{3+}$ -beidellites are frequently found as alteration products of olivine. It is sometimes believed that this transformation is due to a deuteric alteration under special conditions (Allen & Scheid, 1945) but this transformation is usually a result of weathering under poor drainage conditions (Delvigne, 1960; Koster, 1960; Rosler and Wiegmann, 1961; Sherman *et al.*, 1962; Schneiderhorn, 1965; Delvigne, 1965; Wildman *et al.*, 1968; Krishna Murty & Satyana-Rayana, 1969 and 1970; Yaalon, 1970; Trescases, 1975).

The transformation of olivine into nontronite is often accompanied by weathering of the other minerals of the rock into green smectites, in particular of pyroxenes and sometimes of amphiboles. Nontronite and green smectites are also found as filling in joints, cracks and pores in basic and ultramafic weathered rocks.

### 3.2.7.2. *Chemical composition*

The weathering of olivine may give very pure nontronite without aluminium because this element is not present in olivine. With further weathering and the consequent possibility of ion exchange between minerals, the aluminium content can increase progressively in newly formed clay minerals which become ferriferous beidellites. Nontronite may become unstable if superficial weathering descends into deeper layers allowing better drainage conditions. Under such circumstances, silica can be leached, leaving a goethite residue (Trescases, 1975).

### 3.2.7.3. *Optical characteristics*

Under the microscope nontronite appears as a very fine-grained material with yellowish-green to deep green colours. Pleochroism is weak but easily perceptible and the refractive index ranges from 1.56 to 1.61. The obliteration of a single pseudomorph is rarely homogeneous because the secondary flakes are randomly distributed without any relation to the orientation of the original olivine crystal. Nontronite is easily distinguished from chlorite under crossed polarizers, because it has birefringence colours which resemble those of biotite.

### 3.2.7.4. *Micromorphology*

Nontronite in pseudomorphs after olivine (as in pseudomorphs after hypersthene or augite) has a grain size which is frequently heterogeneous and is determined by the internal network of fractures : Nontronite appears as very fine grained material along these fractures and is perpendicular to them. In the cells between the fractures, however, the nontronite is present as large flakes which are either randomly distributed or which form a radiating pattern (see fig. 6).

The volume of nontronite pseudomorphs is variable with their water content. Repeated swelling and shrinkage of this smectite produces divergent cracks around these pseudomorphs. These cracks can then be progressively invaded by secondary materials during wet periods. Adjacent minerals are broken down by colloid plucking during shrinkage of the smectitic embedding materials and thus become more and more susceptible to weathering.

Newly formed goethite acts as a pigment during the first stage of nontronite degradation resulting in colour changes from green or yellowish-green to brown. Minute cryptocrystalline goethite deposits appear in the cracks of the most weathered patches. In the final stage of weathering nontronite pseudomorphs appear as very porous brown

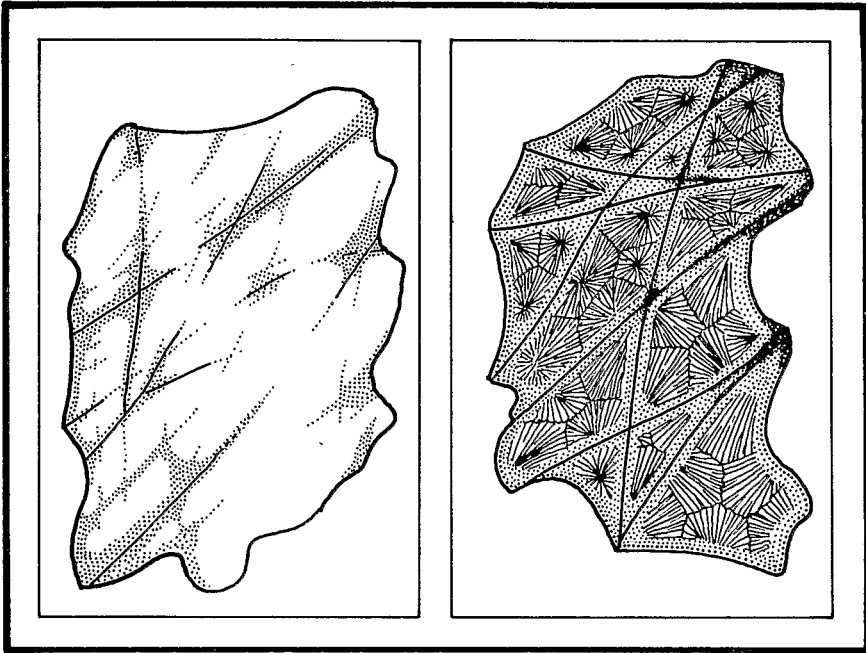


Fig. 6

Olivine alteration into nontronite.

- a. The first stage of olivine alteration under poor drainage conditions in olivine-bearing pyroxenite. An irregular pattern of brown iron hydroxides and poorly crystallized smectite particles can be distinguished along internal cracks and close to the periphery of the olivine mineral.
- b. A completely weathered olivine grain in the same profile. The first stages of weathering are still visible but the inner cores are transformed into well-crystallized smectite lamellae with a deep green colour, strong pleochroism and high birefringence. These smectite flakes are either randomly distributed or, as in the drawing, distributed as radiating units. Irregular brown iron hydroxides are distributed in a honeycomb pattern between these radiating smectite units.

to reddish-brown cellular material, composed of goethite. The goethite particles are randomly distributed and do not follow the original crystallographic directions of the primary olivine because these were destroyed during the intermediate stage in which smectites were formed.

### 3.2.8. Iron hydroxides and ferruginous amorphous materials

#### 3.2.8.1. Occurrence

Olivine is frequently transformed into iron hydroxides and some

times into iron oxides in ferrallitic soils and in weathered rocks under humid tropical conditions and possibly also in temperate climates under very good drainage conditions. Various hydrated and amorphous compounds of silicon and magnesia can also form. Pure goethite or pure haematite pseudomorphs after olivine are often observed in old bauxites formed from basic and ultramafic rocks by weathering and subsequent accumulation processes. These transformation products are very stable, both chemically and mechanically; consequently remnants of goethite and hematite pseudomorphs can often be found embedded in soils or in indurated iron crusts of tropical regions.

The ferruginous pseudomorphs after olivine may have originated in several ways :

- They may consist of a regular goethite network which is associated with irregularly distributed silicon and magnesium components. This transformation is generally transitory during the first stages of ferrallitic weathering, and finally produces pure ferruginous compounds by leaching of silicon and magnesium.
- Under severe leaching conditions all silicon and magnesium are rapidly and directly removed. This leaves some irregular olivine cores surrounded by regularly distributed and usually crystallized iron hydroxide particles.
- It also seems possible that iddingsite may lose its smectitic component after long periods of weathering and leaching. This leaves the goethite component in place. In such cases, it becomes very difficult to distinguish optically, between the original iddingsite and the inherited goethite, because the micromorphological features of both constituents are identical.
- A slow degradation of nontronite pseudomorphs after olivine also gives iron hydroxides. In such cases, however, goethite is not regularly distributed because the inherited network of the original olivine was completely destroyed during the transformation of olivine into nontronite. The colour is also somewhat different and is usually dark brown in iron hydroxides formed by the weathering of nontronite.
- Under moderate leaching and under reducing conditions, in which some of the Fe-components are removed, an open boxwork structure can be formed in weathered olivine. This boxwork consists of amorphous or cryptocrystalline iron hydroxide lamellae which have precipitated along fractures and cleavages or along former crystallographic orientations. This gives rise to polygonal or irregular cells in which small amorphous pellets can be observed even as a coating

material that is colourless to yellowish-creamy and which seems to be composed of a silica-rich hydrated gel.

- Subsequent evolution of the preceding process leads to the formation of a boxwork structure which is entirely ferruginous and encloses numerous empty voids. This structure could be formed by the dissolution of internal amorphous components and the partial recrystallization of iron hydroxide.

Weathering sequences which produce iron hydroxides subsequent to an amorphous phase have for example been observed in soils on basalt of the Vogelsberg area of Germany (Hugenroth *et al.*, 1970), on ultramafic nickeliferous rocks of New Caledonia (Trescases, 1975), and on ultramafic intrusions of the Ivory Coast (Delvigne, 1979).

### 3.2.8.2. Chemical composition

The crystalline component of the iron hydroxides has a composition similar to ordinary goethite or haematite. In the first cryptocrystalline or amorphous stages of weathering, however, water is present in excess when compared with the theoretical formula of the iron compounds. The amorphous components which partly fill the cells of the boxwork structure have a variable composition which depends on : weathering intensity, drainage conditions, possibility of cation exchange between olivine pseudomorphs and their surrounding minerals (uptake of aluminium) and the possibility of a later evolution towards smectite, allophanic material or empty cells.

Iron hydroxide pseudomorphs after olivine extracted from an old bauxite formation in Ivory Coast (see table 2) have a composition which is closest to pure goethite as all silicon and magnesium have been rapidly leached under the strongly ferrallitic conditions. The pseudomorphs have a homogeneous appearance without voids, and the goethite component may have partly inherited the original olivine structure.

Table 2 demonstrates that iron is not leached and that silica is partly removed from completely pseudomorphosed olivines. This can be demonstrated by combining the iron-content of the table with water, which gives goethite and excess water, and by comparing the silica in the weathered product with silica in iddingsite or fresh olivine.

The magnesium content of the completely weathered olivine is very low and is irregularly distributed within the pseudomorph as demonstrated by electron microprobe transects. Small quantities of aluminium have been added, probably brought in from adjacent minerals, and enter the secondary iron minerals as recorded by several

Table 2

Chemical composition of some ferruginous pseudomorphs after olivine on the Ivory Coast (after Delvigne, 1979)

	W. Olv. 1	W. Olv. 2	W. Olv. 3	W. Olv. 4	W. Olv. 5	Bx. Olv.
SiO <sub>2</sub>	13.0	9.4	9.2	8.9	8.8	0.3
TiO <sub>2</sub>	0.1	0.1	0.1	0.1	0.1	0.2
Al <sub>2</sub> O <sub>3</sub>	0.5	1.4	0.7	1.1	0.3	0.6
Fe <sub>2</sub> O <sub>3</sub>	58.4	66.3	65.2	50.9	62.8	83.5
MnO	1.0	0.1	0.1	0.2	1.3	0.2
MgO	0.8	0.4	0.3	0.5	0.4	0.0
CaO	0.7	0.4	0.3	0.5	0.5	0.0
Na <sub>2</sub> O	0.0	0.0	0.1	0.0	0.0	-
K <sub>2</sub> O	0.0	0.0	0.0	0.0	0.2	-
H <sub>2</sub> O <sup>+</sup>	≠25.5	≠21.9	≠24.0	≠37.8	≠25.6	14.9
Total	100.0	100.0	100.0	100.0	100.0	99.7

W. Olv. = olivine weathered into ferruginous material

Bx. Olv. = goethite pseudomorph in bauxite

Fe<sub>2</sub>O<sub>3</sub> = all iron expressed as ferric oxide

1-5 = electron microprobe analyses

Bx. Olv. = ordinary chemical analysis on extracted fragments

- = not analysed

≠ = water calculated by difference.

authors (Norrish & Talyer, 1961; Biais *et al.*, 1972; Nahon, 1976).

Chemical analyses of irregular ferruginous pseudomorphs with a boxwork structure are generally difficult without submicroscopic techniques due to voids, an irregular distribution of the amorphous material inside the cells, the extreme fragility of the samples and the penetration of the synthetic resin into the cellular network during the preparation of the thin sections or polished slides. Huguenot (1970) recorded irregular masses of coarse clayey material in the cells, composed of either opal or an aluminium-silicon-hydrogel ("allophan-opal") of which the SiO<sub>2</sub>/Al<sub>2</sub>O<sub>3</sub> molecular ratio is larger than 3. This could indicate that in such cases SiO<sub>2</sub> removal from the mineral is relatively small when compared with the Al taken up from the outside. Trescases (1975, *op. cit.*) in his work on the weathering of peridotite in New Caledonia, gives a generalized diagram in which he presents, as transitory stages between olivine and goethite, the formation of Si-Fe-containing amorphous material. After Si-leaching this material converts into Fe<sup>3+</sup>-gels and finally converts into crystalline iron hydroxides.

### 3.2.8.3. Micromorphology

In ferrallitic soils and weathered rocks under humid tropical conditions olivine is frequently transformed into a boxwork of iron hydroxides and oxides. The empty cells correspond to the volume of exported material (mainly silicon and magnesium) minus the imported volume of water (Bonifas, 1959). The boxwork is principally inherited from the original internal fracture network of the olivine along which the first steps of weathering occurred. This example is similar to the boxwork in pseudomorphs after pyroxenes and amphiboles formed under similar conditions. In these minerals however the network of iron oxide is mainly inherited from the cleavage-framework. This gives a regular linear pattern (Stoops *et al.*, 1979) which was not derived from a crack-network (irregular linear pattern).

Micromorphological observations of the transformation of olivine into goethite show the following two sequences in moderately drained and well-drained profiles :

– *In moderately drained profiles* and in weathered rocks in which the leaching is not too fast, the final product of olivine weathering consists of a regular, homogeneous, orange to red pseudomorph without pores. This pseudomorph is similar to iddingsite but its colour is often redder. The orientation of the iron hydroxide particles in the pseudomorph is determined by the crystallographic orientation of the primary olivine. The extinction of all goethite particles occurs in a position parallel to the c-axis of the original olivine crystal.

It can often be observed that goethite formation follows the internal cracks of the parent mineral during the early stages of olivine weathering. The goethite then penetrates the olivine cores along their very fine c-cleavages which are invisible in the fresh mineral but are clearly distinguishable as a regular and parallel set of brown lines in the weathered mineral. These brown lines start from the fracture lines and progressively invade the fresh olivine cores. The cores disappear upon ageing but the network of iron hydroxide remains undisturbed. These observations are also valid for pyroxenes and amphiboles in the process of weathering.

Electron microprobe analyses of reddish-brown patches inside olivine cores give few modifications of the chemical composition : ferrous iron oxidizes to ferric iron and the newly formed goethite particles, acting as a pigment, precipitate along inner fractures and cleavage planes. Other cations are not leached. Only iron hydroxide gives some cloudiness to the original transparency of olivine. All

goethite assemblages delimited by internal fractures in a single olivine crystal have the same crystallographic orientation throughout the pseudomorph, and their orientation is the same on both sides of the fractures. During later stages of olivine weathering it seems probable that (see table 2) the goethite component becomes temporarily associated with smectite. The latter component would be responsible for the relatively high content of silicon and magnesium measured, and gives a mineral composition closest to that of iddingsite. With progressive weathering the smectite component dissolves and gradually disappears leaving behind a pure iron hydroxide mineral.

- *In well drained profiles in which leaching is fast*, both silicon and magnesium are exported after an initial stage which is comparable to the previous example. The internal fractures and some cleavage planes are filled with brown cryptocrystalline or amorphous iron hydroxides. This leaves olivine cores which are corroded and surrounded by empty spaces (void coronas) which separate the cores from the ferruginous material in the fractures and cleavages (see fig. 7a).

With the progress of weathering olivine cores disappear leaving a polygonal or irregular pore space which is sometimes partly filled with irregular or botryoidal masses of yellowish to brown coloured amorphous material (see fig. 7b). This amorphous material also eventually disappears. It can often be observed, however, that the ferruginous cell walls become thicker than before. This is probably due to the addition of amorphous iron-containing material, added to the cell walls during weathering.

The ferruginous network which is generally dark brown and amorphous or cryptocrystalline, becomes orange to red and is entirely crystallized in the last stage of pseudomorphism. What is surprising, however, is the fact that all recrystallized parts of the pseudomorph which belong originally to a single olivine grain, have a simultaneous extinction, exactly as if they had been formed during the first stage of weathering. It is very likely that the well-crystallized goethite already existed during the first stage but was masked temporarily by amorphous materials. These went into solution during the later stages of weathering and the first crystallized goethite could appear. The final stage of weathering of olivine consists of a very porous well-crystallized goethite pseudomorph. Small quartz particles are sometimes observed inside the cellular boxwork during the evolution of the amorphous material. These



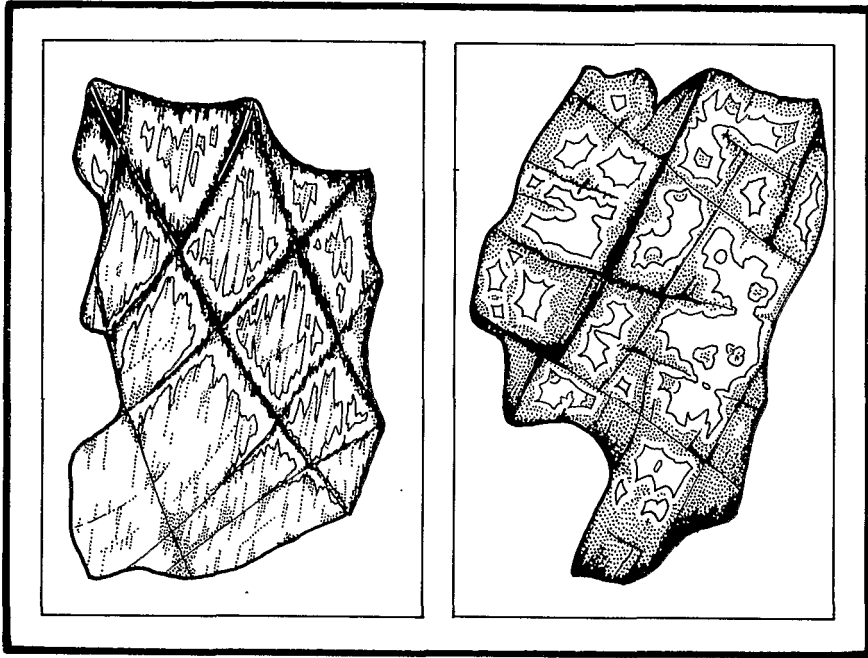


Fig. 7

Olivine alteration into iron hydroxides.

- a. Under good drainage conditions : anhedral olivine crystal in a coarse-grained olivine-bearing pyroxenite which has been partly weathered into iron hydroxides. Iron deposits are visible along the internal fracture planes which delimit a cellular network in which denticulated olivine remnants are progressively replaced by peripheral empty spaces. The olivine grain is replaced by a ferruginous boxwork of empty cells, when completely weathered.
- b. Under moderate drainage conditions : anhedral olivine is also replaced by an irregular ferruginous network, along fractures and cracks, but the inner spaces are temporarily filled by a yellowish-creamy amorphous material which readily dissolves and leaves an empty cellular ferruginous boxwork similar to (a).

quartz grains can remain unaltered for considerable periods. In bauxites derived from basic and ultramafic rocks, the very porous cellular network is often subsequently filled by gibbsite (Allen, 1948; Abbott, 1958).

### 3.3. CONCLUSIONS

Olivines are probably the silicate minerals with the most numerous and diversified alteration products. Very unstable, even under deep magmatic conditions, olivines are among the first minerals to be transformed into secondary minerals characterized by more and more

complex structure when subject to superficial weathering conditions.

### 3.3.1. Crystal chemistry and mineralogy

The unstability of olivine is mainly due to its crystallographic structure in which silica tetrahedra are linked together only by those cations that are easily oxidizable ( $\text{Fe}^{++}$ ) or easily soluble ( $\text{Mg}^{++}$ ). The released tetrahedra, if not leached, form the elementary material necessary for the neoformation of silicate minerals. Isolated tetrahedra can be included more easily into more complex structures than the linked tetrahedra found strongly bound in chain- or framework-silicates.

Depending on conditions in the medium, dissociated elements may combine with each other or with introduced and extraneous elements, - mainly  $\text{H}_2\text{O}$  - to form secondary minerals.

- a) In deeply situated anhydrous but oxidizing media, dissociated tetrahedra may combine to form more complex structures, viz. single-chain silicates in which cations from the original olivine are completely (orthopyroxene) or partially (symplectic magnetite-orthopyroxene) re-utilized. These single-chain silicates may eventually evolve under slightly hydrated conditions, into double-chain silicates (cummingtonite or anthophyllite).
- b) In deeply situated but strongly hydrated media, magnesium phyllosilicates are mainly formed (serpentine) together with iron exsolution and microcrystallization of magnetite.
- c) In less deeply situated hydrated and oxidizing media, phyllosilicates are still formed. Iron may enter into the newly formed mineral lattices (chlorites) or may be partially excluded. In this case, iron may partially inherit the original structure of the olivine, and iddingsite is formed which is a mixed structure of goethite and magnesium smectite.
- d) In the upper-superficial-oxidizing and hydrated media, the speed of leaching of elementary constituents becomes the main factor,  $\text{SiO}_2$ ,  $\text{MgO}$  and  $\text{FeO}$ , the three constituents of olivine, may be combined in different ways, depending mainly on the drainage conditions : nontronite pseudomorphs are formed in closed or poorly drained soils, iron hydroxide pseudomorphs in open systems or in well-drained soils.

### 3.3.2. Geochemistry

In the lattice of the deeply formed olivines,  $\text{Mg}^{++}$  and  $\text{Fe}^{++}$  ions are interchangeable in various proportions and have a similar geo-

chemical behaviour as long as external conditions allow the iron to maintain its ferrous state. In oxidizing conditions however, magnetite (in symplectic association with orthopyroxene) or goethite can form if iron is expelled from the silicate lattices, or ferri-ferrous smectites can form if ferric iron is incorporated into the newly formed products.

Iron is almost always oxidized under surface conditions, and its behaviour may be influenced by other constituents, mainly by silicon.

Experimental weathering studies of olivines (Goni & Leleu, 1971; Pedro & Delmas, 1971), demonstrate the existence of three possible stability fields in the geochemical evolution of magnesian olivines (forsterite). According to the relative speeds of silicon and magnesium removal, residual minerals are formed, the main constituent of which is either silicon or magnesium. If the solubility of both elements is stoichiometric, the entire mineral dissolves. Iron behaviour has been studied less under experimental conditions. Nevertheless it can be assumed that ferrous iron is always transformed into ferric iron under oxidizing conditions. Transformations in this manner may give :

- smectite silicate compounds viz. chlorite and nontronite if magnesium is poorly removed;
- ferruginous minerals, which are rather well crystallized, if both silicon and magnesium are leached;
- amorphous ferri-ferrous silicate materials if silicon is temporarily maintained; these amorphous materials are unstable and subsequent desilicification leads to the formation of goethite.

Iddingsite represents a definite case of the simultaneous formation of a magnesian smectite and goethite which have both inherited the original olivine structure. Iddingsite seems to be unstable under humid tropical conditions and loses its smectitic component. This leaves pure goethite which can eventually be transformed into haematite.

The introduction of extraneous cations (Al, Ti, K, etc.) is observed in pseudomorphs after olivine mainly under superficial weathering conditions and, less frequently, under shallow conditions. Concentrations of trace elements such as Ni are sometimes noticed. The behaviour of these elements under surface conditions is quite different to that of the cations which they diadochically replace under deep or shallow conditions.

The absence of aluminium in olivine considerably reduces the possibility of the formation of Al-containing secondary minerals such as kaolinite and gibbsite, which are frequently formed after other minerals such as feldspars. Nevertheless, kaolinite and gibbsite may appear as pseudomorphs after olivine in some aluminum-rich rocks

such as gabbros and basalts and their bauxitic weathered equivalents.

### 3.3.3. Micromorphology

Practically all olivine crystals, however various the rock types may be, are crossed by irregular and often curved fractures or may contain some extraneous inclusions. These fractures, and planes of weakness and peripheral parts of the mineral can be penetrated by superficial weathering. The propagation of the weathering process seems to be always centripetally directed in olivines whereas in other minerals it may be also centrifugal.

Cleavage planes which are important features in pyroxenes, amphiboles and micas, or internal zonations, which can be found in feldspars or garnets, do not play a dominant role during olivine weathering.

The crystallographic axes and cleavage patterns, which are not usually visible in fresh olivines, can be exceptionally well distinguished during the first alteration stages viz.

- along and on both sides of the internal fractures as reddish-brown microcrystalline alignments; parallel and well-oriented depending on the crystallographic axes of the host mineral during the formation of iddingsite and/or goethite;
- in boxwork structures in which denticulated olivine cores can be temporarily observed, their orientation is parallel to the c-axis of the primary mineral (if this orientation is not disturbed by the formation of empty voids which allows free movement of the olivine cores within the cellular boxwork);
- in “saw-tooth” structures, in which previously formed chlorite flakes are frequently oriented parallel to the sides of the sawteeth or perpendicular to the c-axis of the host-mineral; locally this can give a diamond-shaped structure to the adjacent chlorite booklets;
- in crystallographic orientations of iddingsite from which the extinction position can be parallel to the original extinction position of olivine;
- in lamellar structures developed in pseudomorphs after magnesian olivines, such as bowlingite and saponite: the lamellae were originally oriented perpendicular to the c-axis of the olivine mineral but subsequently slightly disturbed by alternating swelling and shrinkage under the influence of variations in the water content.

In all other cases however the network of cracks and fractures plays the most important role by channeling solution penetration from outside the mineral and influencing the arrangement of secondary minerals.

The most frequent observed secondary structures are the cellular ones. These are irregular and rather well developed. The "septa" are often composed of microcrystalline or amorphous iron oxides and hydroxides and the inner "rooms" are empty when soluble elements are entirely removed, or may be partly filled by amorphous siliceous materials if magnesium is more rapidly exported than silicon. They can also be filled with rather well crystallized nontronite if the original constituents are released in lesser quantities.

#### 4. PROPOSALS

The terms "bowlingite" and "chlorophaeite" should not be used in descriptions, as they are not well enough determined, and seem to correspond partly with other distinct minerals (e.g. saponite or chlorite) and the term "chlorite" should be used cautiously.

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### Summary

Olivine has many alteration products caused by either superficial or deeper seated processes. Alteration products of olivine treated in this paper are : orthopyroxenes, serpentines, iddingsite, chlorite and chloritic minerals, bowlingite and saponite, chlorophaeite, nontronite and ferrous beidellites, iron hydroxides and ferruginous amorphous materials. Olivine is one of the first minerals to weather, mainly due to its crystallographic structure formed by silicon tetrahedra which are linked by easily oxidizable iron and soluble magnesium ions. Isolated silicon tetrahedra, released by weathering, can subsequently form secondary minerals which have a more complex structure than olivine. These processes mainly take place at some depth below the surface of the earth.  $\text{SiO}_2$ ,  $\text{MgO}$  and  $\text{FeO}$  constituents of olivine are usually leached from profiles under superficial conditions and can form for example nontronite in poorly drained soils and iron hydroxides in more open systems. Occurrence, composition, optical characteristics and micromorphology of weathering olivines as well as their pseudomorphs and secondary products, have been considered. The principles and data given in this paper are intended to give more insight into the weathering and neo-formations of minerals in rocks, rock fragments and soils to soil scientists and geologists.

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### Olivines, leurs pseudomorphoses et leurs produits secondaires

#### Résumé

L'olivine peut se transformer en un nombre considérable de minéraux d'altération sous l'influence des facteurs supérogènes ou de processus plus profonds. Parmi les produits d'altération de l'olivine sont traités dans cet article les transformations en orthopyroxène, en serpentine, en iddingsite, en chlorite et minéraux chloriteux, en bowlingite et saponite, en chlorophaeite, en nontronite et beidellites ferrifères, en hydroxydes de fer et en matériaux amorphes. L'olivine est l'un des premiers minéraux à s'altérer et ceci est dû principalement à sa structure cristallographique formée de tétraèdres de silice liés entre eux par des cations magnésium facilement solubilisés ou des cations de fer ferreux facilement oxydés.

Les tétraèdres de silice libérés par altération superficielle peuvent ultérieurement former des minéraux secondaires à structure plus complexe que celle de l'olivine originelle; ces processus prennent place à une certaine profondeur sous la surface de la terre.

Les constituents  $\text{SiO}_2$ ,  $\text{MgO}$  et  $\text{FeO}$  de l'olivine sont habituellement lessivés des niveaux d'altération sous l'influence des conditions superficielles et peuvent éventuellement former de la nontronite dans les sols mal drainés et des hydroxydes de fer dans les milieux plus ouverts.

La répartition, la composition, les propriétés optiques et la micromorphologie des olivines altérées et de leurs pseudomorphoses et minéraux secondaires sont passés en revue. Les résultats livrés dans cet article sont destinés à fournir aux chercheurs en géologie et sciences du sol les informations sur l'altération et les néoformations minérales dans les roches, les altérites et les sols.

## Olivijnen, hun pseudomorfen en sekundaire produkten

### *Samenvatting*

Olivijn kan omgezet worden in een grote verscheidenheid van verweringsprodukten onder de invloed van processen nabij de oppervlakte of dieper in de aardkorst. De volgende omzettingsprodukten van olivijn worden in dit artikel behandeld : orthopyroxenen, serpentijn, iddingsiet, chloriet en chlorietachtige mineralen, bowlingiet en saponiet, chlorophaeiet, nontroniet en ijzerhoudende beidelieten, ijzerhydroxyden en ijzerhoudende amorfe materialen.

Olivijn is een van de gemakkelijkst verweerbare mineralen, hetgeen in hoofdzaak het gevolg is van zijn kristallografische structuur. Deze bestaat uit silicium tetraëders welke onderling verbonden zijn door gemakkelijk oplosbare Mg-ionen en oxydeerbare  $Fe^{++}$ -ionen. De geïsoleerde Si-tetraëders die tijdens de verwerking vrijkomen kunnen vervolgens sekundaire mineralen vormen met een meer komplekse structuur dan olivijn; deze processen vinden plaats op een zekere diepte in de aardkorst. Nabij de oppervlakte worden het  $SiO_2$ , MgO en FeO van de olivijn meestal uitgelooft en kunnen bijvoorbeeld nontroniet vormen in bodems met beperkte drainage en ijzerhydroxyden in meer open systemen. Voorkomen, samenstelling, optische eigenschappen en mikromorphologie van verwerende olivijnen evenals hun pseudomorfen en sekundaire produkten, worden besproken. De gegevens vervat in dit artikel zijn bedoeld om onderzoekers in de aardwetenschappen een beter inzicht te geven in de verwerking en nieuwvorming van mineralen in gesteenten, gesteentefragmenten en bodems.

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**Photo 1.**

**OLIVINE - HYPERSTHENE**

Partial an irregular rim of a symplectitic association of orthopyroxene and magnetite around a fractured olivine core. Intergrowths of subparallel lamellae of alternating magnetite and hypersthene are very characteristic and may remain undisturbed for a long time in weathered rocks and soils. Olivine is colourless and hypersthene lamellae show pleochroism from pink to colourless.

Unweathered CLINOPYROXENITE from Koua Bocca, Ivory Coast.

Plain light, green filter,  
Ocular x 10, Objective x 6,3.

**Photo 2.**

**OLIVINE - SERPENTINE**

Partial alteration of olivine into banded serpentine. Microaggregates and microbanded structures of magnetite are present within the serpentinized areas. The olivine cores belong to a single original crystal which was broken up by trans-, inter- and intramineral fractures. Olivine is colourless whereas serpentine has colours in shades of pale green.

PERIDOTITE from Esterel, France

Plain light, blue filter,  
Ocular x 10, Objective x 6,3.

**Photo 3.**

**SERPENTINE**

Olivine completely transformed into serpentine with a mesh structure and watered appearance. Microaggregates of magnetite are very frequent because the iron from the original olivine is not admitted into the crystal lattice of the newlyformed serpentine and therefore must crystallize into separate individual minerals.

ULTRABASITE from Konakry, Guinea, W. Africa.

Crossed polarizers, green filter,  
Ocular x 10, Objective x 6,3.

**Photo 4.**

**SERPENTINE - MAGNETITE**

Olivine completely transformed into fibrous serpentine with a radiating structure. Minute magnetite particles are mainly concentrated nearest to the original grain limits and between radiating units with several small apatite crystals. These are formed during serpentinizing metamorphic processes.

PYROXENITE from Koua Bocca, Ivory Coast.

Plain light, green filter,  
Ocular x 10, Objective x 6,3.



**Photo 5.**

**OLIVINE - IDDINGSITE**

Regular iddingsite rim around an olivine crystal. The external limit of the iddingsitized rim corresponds to the original limit of the euhedral olivine crystal whereas the inner limit is more irregular. Several iddingsite indentations invade the olivine core and follow sub-parallel planes perpendicular to the c-axis of the host-mineral.

BASALT from Kivu, Zaïre  
Plain light, orange filter,  
Ocular x 10, Objective x 25.

**Photo 6.**

**OLIVINE - IDDINGSITE**

Another view of a more or less regular rim of reddish-brown iddingsite around olivine crystals. The transformation is a little more complete and the olivine core is finely denticulated. In these two cases, iddingsitization proceeds along external crystal faces and progressively invades all olivine remnants.

BASALT from Auvergne, France  
Plain light, orange filter,  
Ocular x 10, Objective x 16.

**Photo 7.**

**OLIVINE - IDDINGSITE**

Partial and irregular transformation of olivine into reddish-brown iddingsite. The secondary mineral penetrates into the olivine from the outer limits but also follows intramineral fractures and in doing so delimits several irregular cores. This process is frequently seen in coarse grained rocks.

CLINOPYROXENITE from Koua  
Bocca, Ivory Coast.  
Plain light, red filter,  
Ocular x 10, Objective x 2,5.

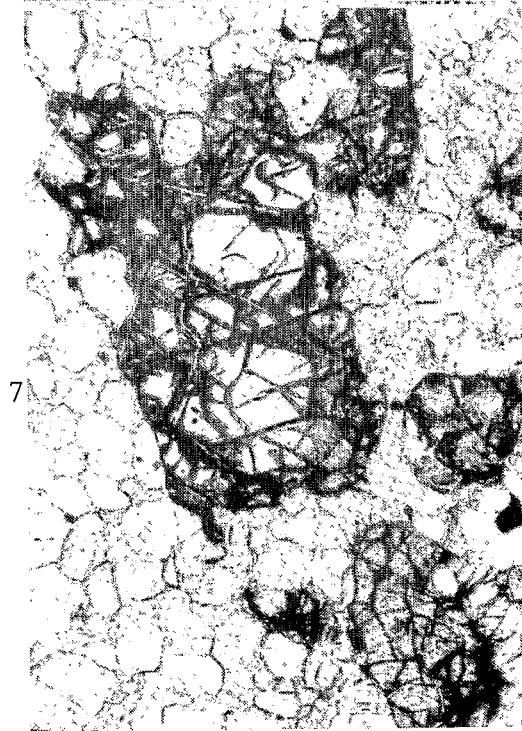
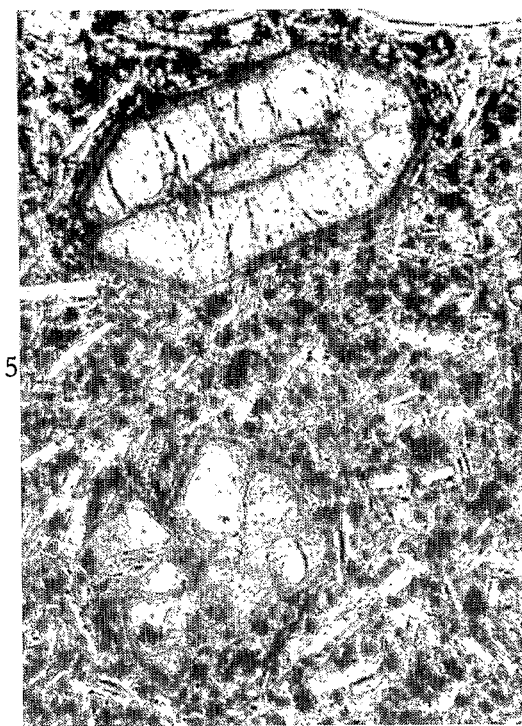
**Photo 8.**

**OLIVINE - IDDINGSITE**

Almost complete transformation of olivine into iddingsite. Traces of early deposited magnetite in internal fractures are clearly visible within the iddingsitized areas. Traces of concentric growth around olivine cores are expressed by the alternating pale and dark reddish colours of the surrounding iddingsite.

CLINOPYROXENITE from Koua  
Bocca, Ivory Coast.  
Plain light, red filter,  
Ocular x 10, Objective x 6,3.





**Photo 9.**

**IDDINGSITE**

Olivine completely transformed into iddingsite. The secondary mineral has a reddish-brown colour and exhibits a distinct micaceous cleavage. The cleavage in this sample is probably slightly emphasized by shrinkage during thin section preparation but it is clear that the micaceous cleavage is partly inherited from the original crystallographic structure of olivine : the whole iddingsitized area forms a single crystal.

**CLINOPYROXENITE** from Koua

Bocca, Ivory Coast.

Plain light, orange filter,

Ocular x 10, Objective x 6,3.

**Photo 10.**

**CHLORITE - BOWLINGITE**

Partial alteration of olivine in the form of a definite "saw tooth" structure. The green chlorite (dark grey on the photo) is crystallized into well-oriented flakes perpendicular to the intramineral fracture, whereas bowlingite-saponite (pale grey on the photo), with a well developed micaceous cleavage, has flakes either parallel to the "saw tooth" sides or perpendicular to the long axis of the host mineral. Bowlingite exhibits a beige colour and a weak pleochroism.

**BASALT** from Kivu, Zaïre.

Plain light, green filter,

Ocular x 10, Objective x 16.

**Photo 11.**

**CHLORITE - BOWLINGITE**

Olivine crystal which is largely replaced by a "saw-tooth" structure that contains chlorite and bowlingite, similar to the secondary minerals in the preceding picture. The orientation of green chloritic flakes is quite different from those of beige bowlingite as emphasized in the next photo which was taken with crossed polarizers.

**BASALT** from Kivu, Zaïre

Plain light, green filter,

Ocular x 10, Objective x 16.

**Photo 12.**

**CHLORITE - BOWLINGITE**

Same area as in photo 11. The different orientations of chloritic and smectitic flakes are clearly visible, under crossed polarizers particularly because of the much higher birefringence of the smectitic component than that of the chloritic flakes.

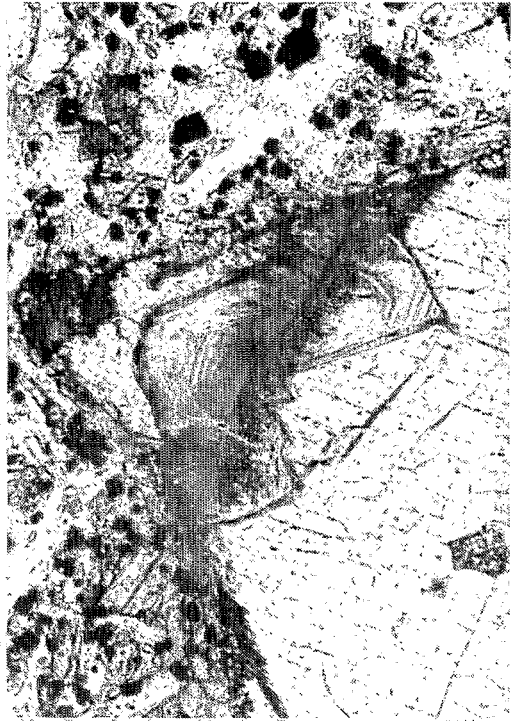
**BASALT** from Kivu, Zaïre.

Crossed polarizers, no filter,

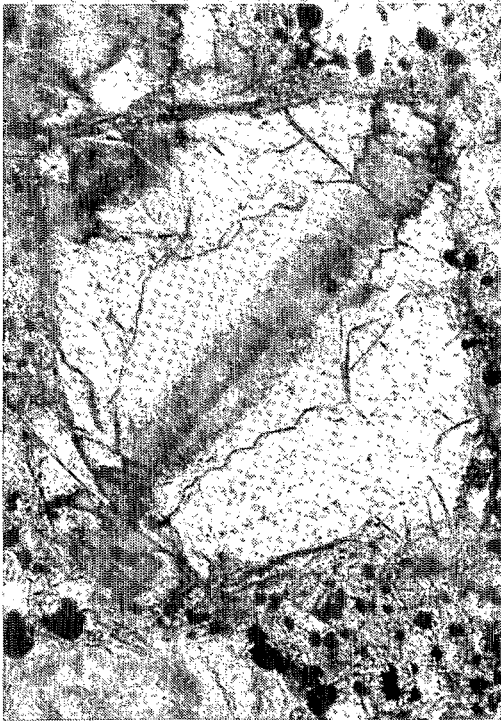
Ocular x 10, Objective x 16.



9



10



11



12

**Photo 13.**

**CHLORITE-IRON HYDROXIDES**

Two-phase transformation of a single olivine crystal into yellowish-brown chlorite (by a deuteric process) which is pale grey on the photo, and into dark brown iron hydroxides (by weathering) which is dark grey to almost black on the photo. The transformation structures are quite different : a "saw-tooth" pattern between the olivine and chlorite, and dark brown lineations of iron compounds which invade the olivine core and follow the crystallographic orientations of the host mineral.

CLINOPYROXENITE from Koua  
Bocca, Ivory Coast.  
Plain light, yellow filter,  
Ocular x 10, Objective x 6,3.

**Photo 15.**

**SERPENTINE-IDDINGSITE**

Olivine is transformed into twin bands of serpentine (white on photo) along sub-parallel and anastomosing trans-mineral fractures, which contain a deposit of magnetite in their centres. Most of the delimited olivine cores are later transformed into brownish-red iddingsite (dark grey on photo). Several untransformed olivine cores can be distinguished in the upper-left part of the crystal.

CLINOPYROXENITE from Koua  
Bocca, Ivory Coast.  
Plain light, green filter,  
Ocular x 10, Objective x 6,3.

**Photo 14.**

**ANTIGORITE-CHLORITE-BOWLINGITE**

Three-phase transformation of a single olivine crystal : some internal fractures are followed by fine antigorite crystallizations (colourless on the photo) with fibrous elements perpendicular oriented to the fracture. The contact is finely denticulated. Chlorite (dark grey) follows serpentinized zones and some new fractures with coarse denticulated limits. In the more transformed areas, smectite appears (pale grey) as large flakes alternating with chloritic material.

BASALT from Kivu, Zaïrè.

Plain light, green filter,  
Ocular x 10, Objective x 16.

**Photo 16.**

**ANTIGORITE-CHLORITE-  
BOWLINGITE-NONTRONITE**

Polyphased transformation of olivine in the weathered cortex of a basaltic boulder. Antigorite (white), chlorite (dark grey), bowlingite (medium grey) are developed along previous fractures, whereas nontronite (pale grey) surrounds the finely denticulated unweathered olivine core. Several palagonitic areas are visible in the finegrained basaltic part.

BASALT from Kivu, Zaïre.

Plain light, green filter,  
Ocular x 10, Objective x 6,3.

13



14



15



16



**Photo 17.**

**BOWLINGITE-SAPONITE**

Olivine completely transformed under shallow depth conditions into very homogeneous smectitic material surrounded by a thin dark brown deposit of iron compounds. The colour of the smectite is yellowish-beige with a weak pleochroism. Thin previous fractures are surrounded by finely denticulated chloritic material with a pale green colour.

**CLINOPYROXENITE** from Koua  
Bocca, Ivory Coast.  
Plain light, green filter,  
Ocular x 10, Objective x 6,3.

**Photo 18.**

**BOWLINGITE-SAPONITE**

Same area as in photo 17. The smectitic mineral is well crystallized into large flakes, with a high birefringence and particularly well oriented throughout the whole crystal. Several voids are visible but it is not obvious if they were present under natural conditions in the rock before treatment. Diopsidic augite which is partly weathered into yellow montmorillonite can also be distinguished.

**CLINOPYROXENITE** from Koua  
Bocca, Ivory Coast.  
Crossed polarizers, no filter.  
Ocular x 10, Objective x 6,3.

**Photo 19.**

**NONTRONITE**

Olivine crystal completely weathered into brownish green nontronite. The transformation has followed numerous internal fractures which are still visible with their brown coatings of iron hydroxides. Bordering the former olivine crystal one can observe a remnant of the symplectitic structure composed of magnetite lamellae within an unweathered orthopyroxene crystal.

**CLINOPYROXENITE** from Koua  
Bocca, Ivory Coast.  
Plain light, yellow filter,  
Ocular x 10, Objective x 6,3.

**Photo 20.**

**NONTRONITE**

Same area as in photo 19. Nontronite appears well crystallized but the flakes are very small compared to the smectite minerals of photo 18. In each cell formed by the boxwork structure, nontronite is well oriented as seen by the ferruginous coatings but is perpendicular to them whereas nontronite flakes in the central parts of the cells are randomly distributed.

**CLINOPYROXENITE** from Koua  
Bocca, Ivory Coast.  
Crossed polarizers, no filter,  
Ocular x 10, Objective x 6,3.

17



18



19



20



**Photo 21.**

**IRON HYDROXIDES**

Weathering starts with the formation of dark brown, badly crystallized, iron hydroxides. These invade the olivine crystal following a preferential orientation and determine a finely denticulated shape. The iron compounds are probably amorphous and appear completely dark under crossed polarizers during rotation of the stage. The pseudohexagonal crystal included in the iron hydroxides is clinopyroxene.

**CLINOPYROXENITE** from Koua

Bocca, Ivory Coast

Plain light, orange filter,

Ocular x 10, Objective x 6,3.

**Photo 22.**

**IRON HYDROXIDES AND OXIDES**

Dark, almost black, ferruginous impregnation of previously formed serpentine and chlorite along fractures in an olivine crystal. Some banded phyllosilicates are still recognizable, whereas other areas are completely obscured. As in the preceding example, iron penetrates the fresh olivine along an internal cleavage network, and produces finely denticulated mineral remnants.

**BASALT** from Kivu, Zaïre

Plain light, green filter,

Ocular x 10, Objective x 2,5.

**Photo 23.**

**GOETHITE-HEMATITE-GIBBSITE**

Boxwork structure after olivine in a bauxite sample. An early formed fracture network forms the walls of the cells and is composed of hematite (black on the photo). The cells are partly filled with authigenic and large crystals of goethite (pale grey on the photo). The orientation of the goethite crystals is the same for all cells in one olivine grain. The central voids were later filled by allogenic gibbsite (white) whereas goethite was partly transformed into hematite (black internal borders).

**BAUXITE** after **CLINOPYROXENITE**

from Koua Bocca, Ivory Coast

Plain light, yellow filter,

Ocular x 10, Objective x 16.

**Photo 24.**

**GOETHITE-HEMATITE**

Olivine completely pseudomorphosed into iddingsite. After the first step of transformation, iddingsite itself loses its smectitic component during weathering and soil formation. Only the ferruginous component remains while keeping its original orientation which was inherited from olivine and maintained during the provisional iddingsite stage. The pseudomorph is bright red in colour and the early formed magnetite deposits are still visible along the fracture network.

**WEATHERED CLINOPYROXENITE**

from Koua Bocca, Ivory Coast

Plain light, red filter,

Ocular x 10, Objective x 6,3.



21



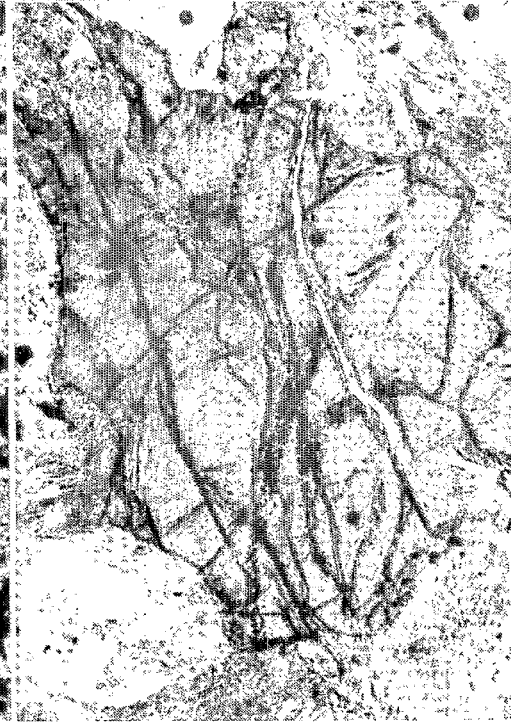
22



23



24



**Photo 25.**

**GOETHITE-HEMATITE**

Olivine grain which was initially composed of two imbricated but distinct crystals each of which having its own crystallographic orientation. After the first transformation step into iddingsite, they were weathered into goethite by the loss of their smectitic component and subsequently dehydrated into hematite. However, both original components have maintained their own crystallographic orientation throughout the three successive alteration phases as shown by the two following photos.

**WEATHERED CLINOPYROXENITE**

from Koua Bocca, Ivory Coast

Plain light, red filter,

Ocular x 10, Objective x 2,5.

**Photo 26.**

**GOETHITE-HEMATITE**

Same area seen as on the preceding photo. The stage was rotated until one of the two components was completely in an extinction position whereas the second crystal remained visible.

**WEATHERED CLINOPYROXENITE**

from Koua Bocca, Ivory Coast

Crossed polarizers, orange filter,

Ocular x 10, Objective x 2,5.

**Photo 27.**

**GOETHITE-HEMATITE**

Same area as on the two preceding photos. The microscope stage was rotated symmetrically compared to that of photo 26, so that the first component was visible and the second in extinction. External grains of clinopyroxene are partly weathered into montmorillonite which surrounds finely denticulated pyroxene cores. Note the high birefringence of the clay minerals and their orientations inherited from the original crystallographic lattices.

**WEATHERED CLINOPYROXENITE**

from Koua Bocca, Ivory Coast.

Crossed polarizers, orange filter,

Ocular x 10, Objective x 2,5.

**Photo 28.**

**GOETHITE-HEMATITE**

Early formed iddingsite after olivine is partly transformed into goethite. Some remnants of iddingsite are still recognizable (dark grey) on the right of the photo, whereas the center of the grain and its left part are completely transformed into bright yellow goethite. The extinction position is the same for the two components. Note the presence of a symplectitic structure of magnetite and nontronite (after hypersthene).

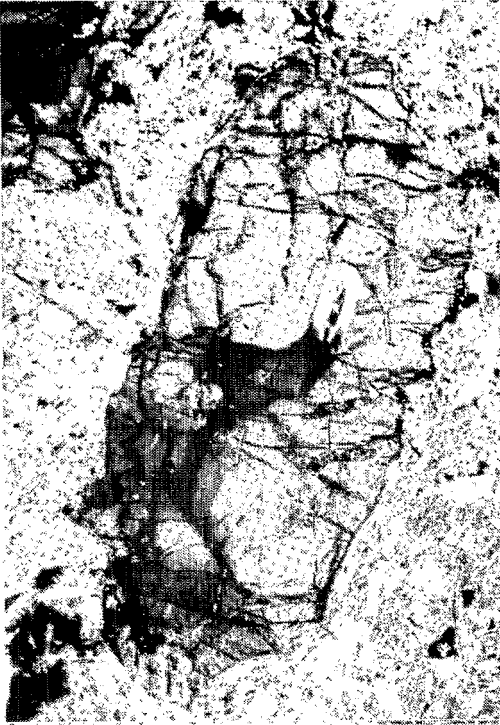
**WEATHERED CLINOPYROXENITE**

Koua Bocca, Ivory Coast.

Plain light, orange filter,

Ocular x 10, Objective x 6,3.

25



26



27



28



**Photo 29.**

**COLOURLESS SILICEOUS GELS**

Open boxwork structure which is partly filled by authigenic siliceous amorphous material after olivine in a slightly weathered cortex on rock boulder. Some original fractures are still recognizable. These are polymineralic with pale brown iron hydroxide in the fracture central plane, yellowish chloritic material on both sides (medium grey); the cell walls are coated by iron oxide (black on the photo) and then by amorphous colourless material. The central part of the cells is empty.

CLINOPYROXENITE from Koua  
Bocca, Ivory Coast.  
Plain light, green filter,  
Ocular x 10, Objective x 6,3.

**Photo 31.**

**OLIVINE-AMORPHOUS MAT.**

First step of olivine transformation into amorphous material. Some olivine remnants appear (pure white) unweathered within a completely pseudomorphosed area. Alteration penetrates the mineral from the fracture network and follows a secondary subparallel network of narrow fissures which is slightly stained by ferruginous compounds.

CLINOPYROXENITE from Koua  
Bocca, Ivory Coast.  
Plain light, green filter,  
Ocular x 10, Objective x 16.

**Photo 30.**

**COLOURLESS SILICEOUS GELS**

Olivine crystal in a slightly weathered cortex on basaltic boulder partially pseudomorphosed into chloritic material (dark grey) during a first alteration step and subsequently weathered into colourless siliceous amorphous material (very pale grey). Note that the amorphous material occupies nearly all areas free from chlorite and there are only a few voids (pure white on the photo).

BASALT from Kivu, Zaïre.

Plain light, green filter,  
Ocular x 10, Objective x 6,3.

**Photo 32.**

**IRON-STAINED AMORPHOUS MAT.**

Irregular boxwork after olivine. It is partly filled by amorphous material, partly colourless and partly stained by microcrystalline or amorphous iron hydroxides (cf. details on the next photo). The surrounding grey mineral is poikilitic greenish-brown hornblende which includes diopside (white) and magnetite (black).

CLINOPYROXENITE from Koua  
Bocca, Ivory Coast.  
Plain light, green filter,  
Ocular x 10, Objective x 6,3.

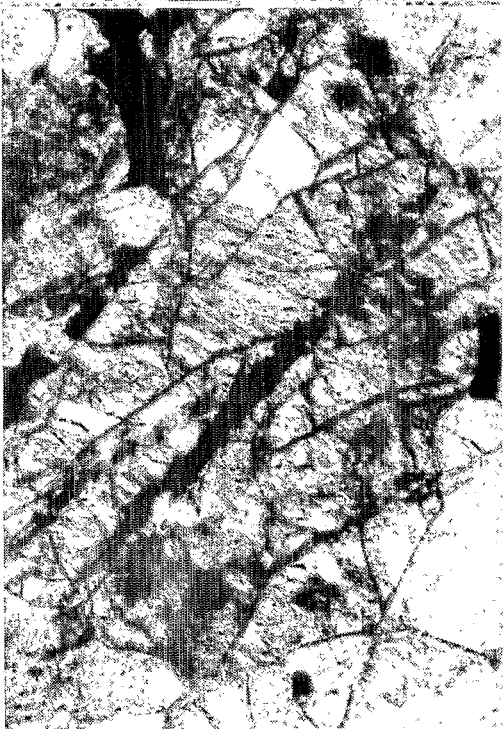
29



30



31



32



**Photo 33.**

**Si-Fe AMORPHOUS MATERIAL**

Detailed view of a ferruginous boxwork structure after olivine. It shows the internal disposition of variously stained amorphous materials (pale to dark grey) which are arranged as irregular coatings against the dividing walls that were formed according to the original fracture network. Most of the cells are partly occupied by weathering products which surround an irregular empty space in the centre.

CLINOPYROXENITE from Koua

Bocca, Ivory Coast

Plain light, green filter,

Ocular x 10, Objective x 16.

**Photo 34.**

**FERRUGINOUS AMORPHOUS MAT.**

Olivine crystal partly weathered into reddish-brown amorphous material in a slightly weathered cortex on a basaltic boulder. Several irregular cavernous olivine cores are still distinguishable in the less weathered part of the grain. Amorphous Si-Fe material is re-arranged into botryoidal masses surrounding an irregular empty space on the opposite side.

BASALT from Kivu, Zaïre.

Plain light, orange filter,

Ocular x 10, Objective x 16.

**Photo 35.**

**SERPENTINE-IDDINGSITE**

Two-phase alteration of an olivine crystal into serpentine followed by a later transformation of olivine remnants into iddingsite. Several minute irregular olivine cores are still recognizable in the central part of the photo (colourless). These are completely surrounded by reddish-brown iddingsite (dark grey) nearly black. Some minute magnetite deposits are visible along the external border of the serpentinized area.

CLINOPYROXENITE from Koua

Bocca, Ivory Coast.

Plain light, green filter,

Ocular x 10, Objective x 2,5.

**Photo 36.**

**SERPENTINE-SMECTITE**

Two-phase transformation of an olivine crystal in a partly weathered rock. Olivine is completely pseudomorphosed into serpentine during the first step, with magnetite exsolutions along the grain limits and along the inner fractures. The serpentine minerals are subsequently weathered into greenish clays (exact composition undetermined) which did not retain any orientation inherited from the original mineral because the serpentine in the previous stage was already randomly distributed.

CLINOPYROXENITE from Koua

Bocca, Ivory Coast.

Plain light, green filter,

Ocular x 10, Objective x 6,3.

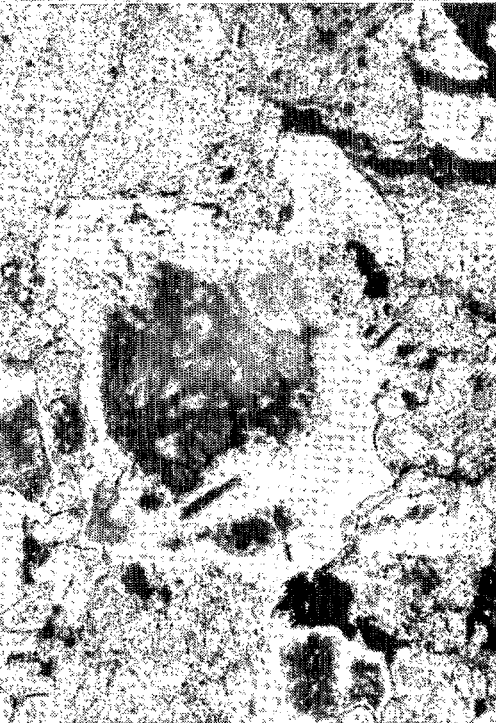
33



34



35



36

