NRTS-25/UNUP-505

The Impacts of Opencast Mining on the Rivers and Coasts of New Caledonia

Eric C.F. Bird, Jean-Paul Dubois, and Jacques A. Iltis

THE UNITED NATIONS UNIVERSITY

From the CHARTER OF THE UNITED NATIONS UNIVERSITY

ARTICLE I

Purposes and structure

1. The United Nations University shall be an international community of scholars, engaged in research, post-graduate training and dissemination of knowledge in furtherance of the purposes and principles of the Charter of the United Nations. In achieving its stated objectives, it shall function under the joint sponsorship of the United Nations and the United Nations Educational, Scientific and Cultural Organization (hereinafter referred to as UNESCO), through a central programming and co-ordinating body and a network of research and post-graduate training centres and programmes located in the developed and developing countries.

2. The University shall devote its work to research into the pressing global problems of human survival, development and welfare that are the concern of the United Nations and its agencies, with due attention to the social sciences and the humanities as well as natural sciences, pure and applied.

3. The research programmes of the institutions of the University shall include, among other subjects, coexistence between peoples having different cultures, languages and social systems; peaceful relations between States and the maintenance of peace and security; human rights; economic and social change and development; the environment and the proper use of resources; basic scientific research and the application of the results of science and technology in the interests of development; and universal human values related to the improvement of the quality of life.

4. The University shall disseminate the knowledge gained in its activities to the United Nations and its agencies, to scholars and to the public, in order to increase dynamic interaction in the world-wide community of learning and research.

5. The University and all those who work in it shall act in accordance with the spirit of the provisions of the Charter of the United Nations and the Constitution of UNESCO and with the fundamental principles of contemporary international law.

6. The University shall have as a central objective of its research and training centres and programmes the continuing growth of vigorous academic and scientific communities everywhere and particularly in the developing countries, devoted to their vital needs in the fields of learning and research within the framework of the aims assigned to those centres and programmes in the present Charter. It shall endeavour to alleviate the intellectual isolation of persons in such communities in the developing countries which might otherwise become a reason for their moving to developed countries.

7. In its post-graduate training the University shall assist scholars, especially young scholars, to participate in research in order to increase their capability to contribute to the extension, application and diffusion of knowledge. The University may also undertake the training of persons who will serve in international or national technical assistance programmes, particularly in regard to an interdisciplinary approach to the problems with which they will be called upon to deal.

ARTICLE II

Academic freedom and autonomy

1. The University shall enjoy autonomy within the framework of the United Nations. It shall also enjoy the academic fredom required for the achievement of its objectives, with particular reference to the choice of subjects and methods of research and training, the selection of persons and institutions to share in its tasks, and freedom of expression. The University shall decide freely on the use of the financial resources allocated for the execution of its functions. . . .

NRTS-25/UNUP-505

THE IMPACTS OF OPENCAST MINING ON THE RIVERS AND COASTS OF NEW CALEDONIA

THE UNITED NATIONS UNIVERSITY

Eric C.F. Bird — Department of Geography, University of Melbourne, Parkville, Victoria, Australia

Jean-Paul Dubois — Section Géographie, ORSTOM, Nouméa, New Caledonia

Jacques A. Iltis — Section Géographie, ORSTOM, Nouméa, New Caledonia

NRTS-25/UNUP-505
ISBN 92-808-0505-3

This report was prepared under the auspices of the Development Studies Division of the United Nations University. The views expressed are those of the authors and not necessarily those of the United Nations University.

The United Nations University
Toho Seimei Building, 15-1 Shibuya 2-chome, Shibuya-ku, Tokyo 150, Japan
Tel: (03) 499-2811 Telex: J25442 Cable: UNATUNIV TOKYO

Printed in Japan 9

CONTENTS

FIGURES, PLATES, AND TABLES

Figures

Plates

Tables

PREFACE

Mineral exploitation, especially of nickel and chromium ores, and to a lesser extent of iron, cobalt, manganese, and coal, has been the essential basis on which the economy of New Caledonia (an Overseas Territory of the Republic of France) has developed during the past century. Within this period the production of nickel from New Caledonia has represented a significant proportion of world nickel production, exceeded only by that of Canada and, at times, by that of the Soviet Union. Extraction of nickel and iron ores by opencast mining has been extensive in New Caledonia, and, as many of the sites where these ores occur are on hilltops, there has been a major impact on the island's landscape. Mining waste generated from opencast hilltop workings has spread down slopes into bordering valleys, into river channels, and thence to the coast, in some cases filling in river mouths, augmenting deltas, and modifying the sediments and ecology of the nearshore areas.

Our aim in the present monograph has been to document the extent of this landscape modification in terms of the history of mining in New Caledonia and of economic factors that have influenced its development, and fluctuations in its intensity. The first chapter describes the environmental context, with special reference to geomorphology. The second reviews the history of mining activity in economic terms. The third examines each of the major river catchments of New Caledonia and traces the extent and impacts of mining activities, and the fourth considers mining in terms of landscape management, outlining some possible developments in the future.

Within the scope of such a review, we can do no more than indicate the geomorphological, sedimentological, and ecological consequences of mining and the dispersal of mining waste materials in New Caledonia. Our aim has been to present the overall picture. Detailed, local studies and assessments must follow.

We are grateful to the United Nations University, whose project on coastal resources management focused attention on coastal environments in New Caledonia; to the Office de la Recherche Scientifique et Technique Outre-Mer in Nouméa, which supported field research and documentation; and to the Société Métallurgique Le Nickel (SLN), especially MM. Le Goff and Cheyrezy, who provided permits and information. We also thank a number of colleagues, including Teh Tiong Sa of the University of Malaysia, Kuala Lumpur, for discussions and scientific advice; M. Philippe Ribère, photographer of the ORSTOM Centre in Nouméa; and Mr. Robert Bartlett and Miss Wendy Godber, Department of Geography, University of Melbourne, for the preparation of maps, diagrams, and photographs.

Eric C.F. Bird
Jean-Paul Dubois
Jacques A. Iltis

1. LANDFORM EVOLUTION IN NEW CALEDONIA

New Caledonia is an island group in the south-west Pacific consisting of one large mountainous island (known as La Grande Terre; area: 16,750 sq km) and over a hundred small associated islands, including the Iles Belep to the north-west and the Ile des Pins to the south-east. Its coastlines, about 1,000 km long, are bordered by extensive coral reefs, including major barrier reef systems off the east and west coasts (fig. 1). The east coast is generally steep and mountainous, while the west coast has foothills and wider coastal plains. Major river systems are shown in figure 2.

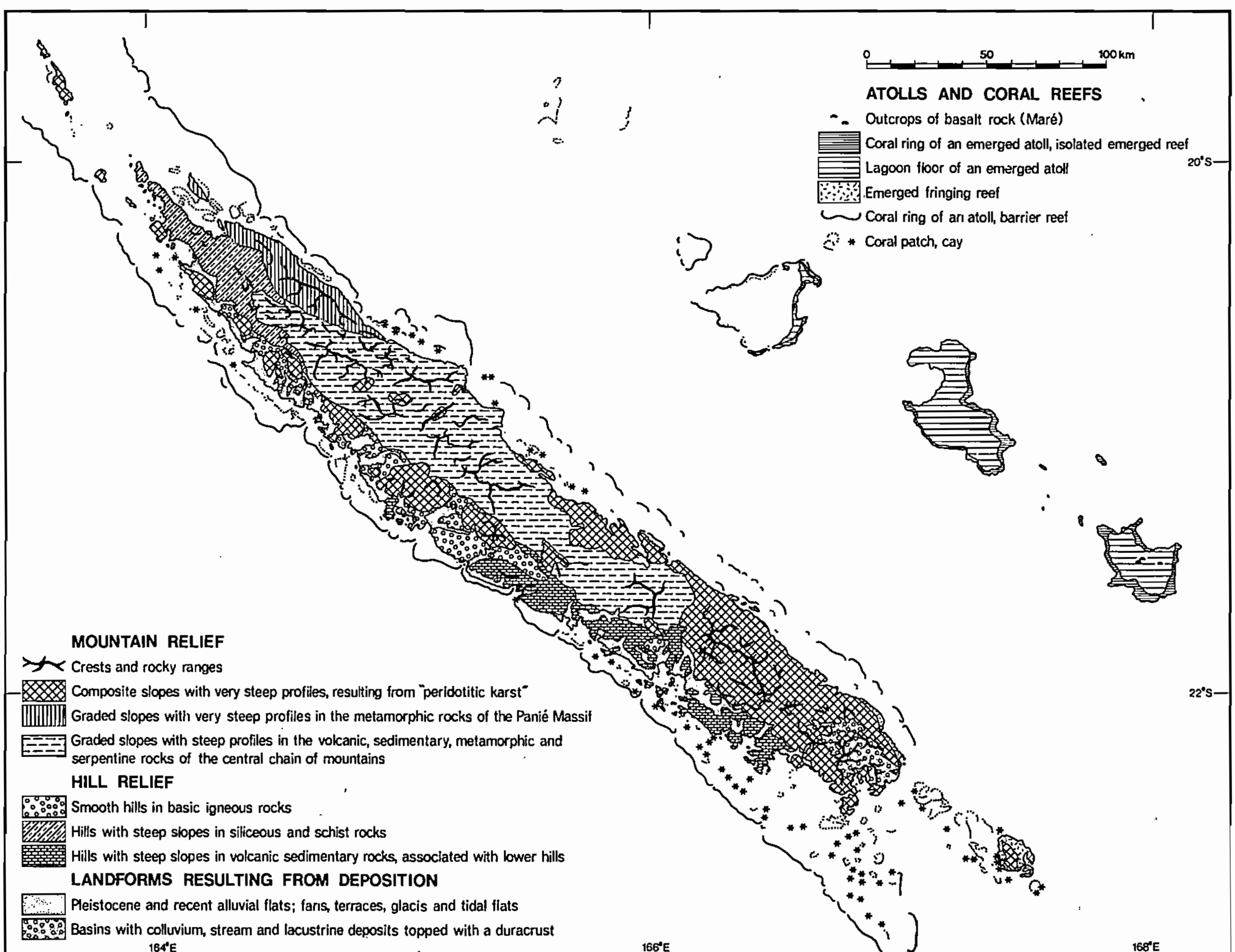

FIG. 1. Geomorphology of New Caledonia

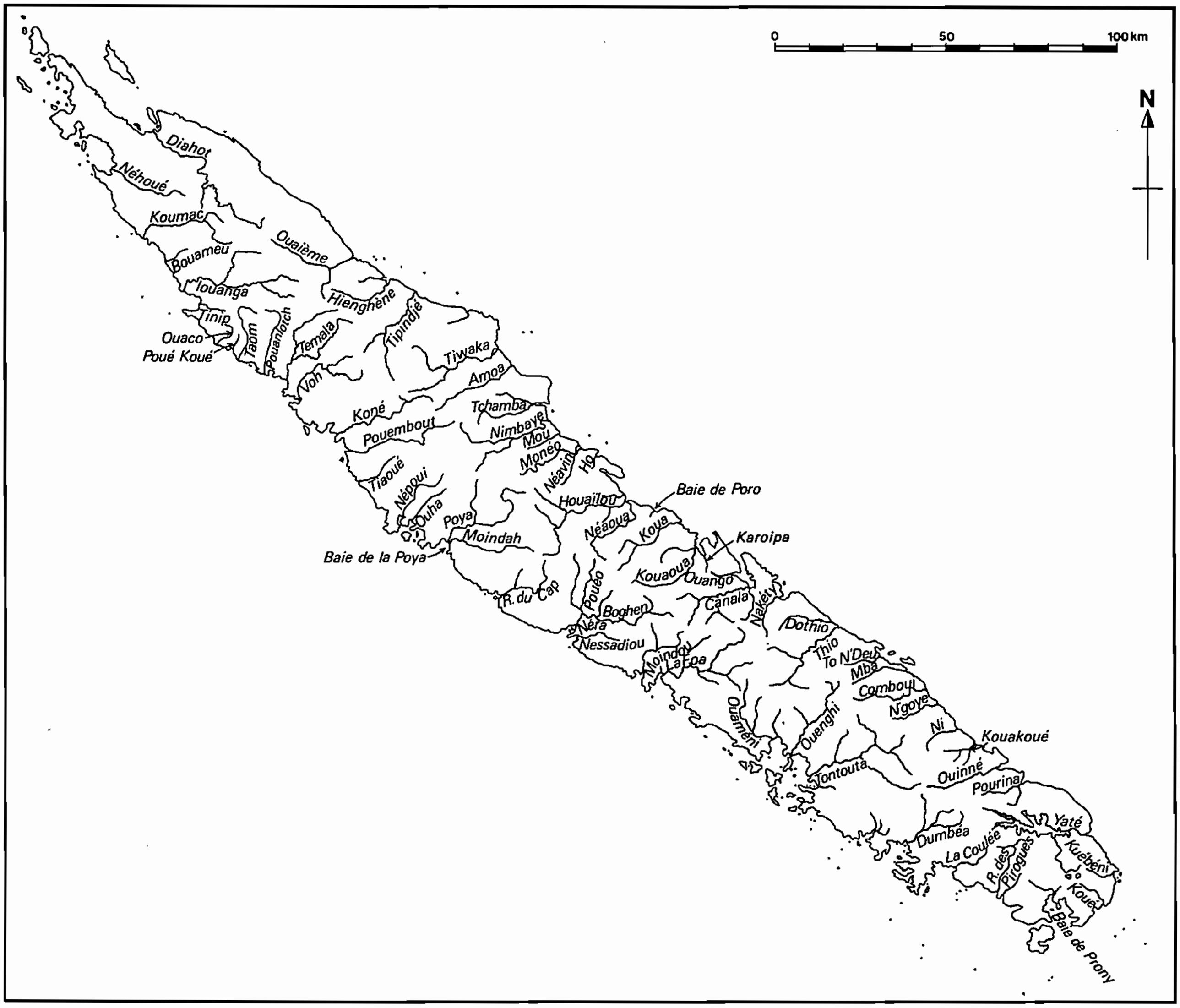

FIG. 2. Major River Systems in New Caledonia

Lying just north of the Tropic of Capricorn, New Caledonia has a generally warm and equable climate, with cooler conditions in the interior uplands; south-easterly trade winds prevail for much of the year, producing annual rainfalls of more than 2,000 mm on much of the east coast, rising to more than 3,000 mm in mountain ranges, while the west coast, in rain shadow, receives less than 1,000 mm. There is a winter dry season which lengthens and intensifies northwards, especially along the west coast, where some areas have warm semi-arid climates and are subject to prolonged droughts. Tables 1 and 2 give the mean monthly temperature and rainfall data for selected stations. In the summer months recurrent depressions bring hot and wet conditions, and occasionally tropical cyclones move from the north or north-east across New Caledonia, bringing violent winds and torrential rains followed by extensive river flooding. The most recent of these was Cyclone Gyan, which crossed northern New Caledonia at Christmas 1981, bringing winds of up to 170 km per hour at Koumac, where 429.7 mm of rain fell in one day; at Kaala-Gomen, to the south-east, this cyclone brought over 500 mm of rainfall; and heavy downpours were registered at many stations in the northern half of the island, followed by extensive river flooding.

It is likely that the natural vegetation of New Caledonia was largely forest (rain forest on the mountain ranges and along the wetter east coast; sclerophyllous forest on the west coast) giving

TABLE 1. Mean Monthly Temperatures (°C) for Selected Stations, 1956–1975

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Nouméa	25.8	26.1	25.6	23.8	22.3	21.0	19.9	20.0	20.8	22.2	23.7	25.1	23.0
La Tontouta	25.8	26.0	25.4	23.3	21.5	20.1	18.9	19.1	20.0	21.6	23.5	25.0	22.5
Ouaco	25.9	26.2	26.0	24.1	22.4	21.2	20.3	20.3	21.0	22.4	23.9	25.0	23.2
Yaté	24.9	25.4	24.9	23.3	21.7	20.4	19.1	19.3	20.1	21.4	22.9	24.1	22.3
Thio	25.5	25.8	25.5	23.6	22.0	20.7	19.6	19.9	20.7	21.9	23.4	24.5	22.8
Hienghène	26.0	26.3	25.9	24.4	22.7	21.4	20.3	20.4	21.3	22.7	24.1	25.2	23.4

Source: National Meteorological Office

TABLE 2. Mean Monthly Rainfall (mm) for Selected Stations, 1956–1975

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual total
Nouméa	121.1	114.1	127.0	113.8	89.9	125.9	70.0	72.9	43.7	44.8	49.7	47.4	1,020.3
La Tontouta	137.9	149.2	128.1	88.7	79.6	105.3	66.2	62.0	38.9	37.5	48.7	57.7	999.8
Poya	224.2	182.9	162.7	109.3	78.4	86.8	68.4	59.1	50.7	42.6	75.1	74.7	1,214.9
Ouaco	114.6	124.6	103.6	54.7	77.9	75.4	54.3	43.3	38.0	29.3	34.8	61.6	812.1
Col d'Amieu	260.2	308.6	255.8	174.3	102.7	169.1	96.5	78.5	77.4	53.7	98.3	112.7	1,787.8
Yaté	414.8	389.6	361.7	346.2	207.2	278.8	195.7	170.8	149.0	103.3	188.5	180.1	2,985.7
Thio	318.4	256.6	260.7	177.0	162.3	185.1	116.4	85.5	86.7	71.6	97.2	108.2	1,925.7
Houaïlou	330.8	269.8	291.8	194.9	119.2	163.0	117.0	91.9	80.4	68.0	117.5	158.9	2,003.2
Tiwaka	542.5	419.2	467.0	329.8	188.6	262.4	190.5	139.4	119.5	119.3	207.4	221.2	3,206.8
Hienghène	400.5	332.7	375.1	198.6	169.7	170.3	122.4	100.4	88.0	79.2	135.4	170.1	2,342.4

Source: National Meteorological Office

place over about 30 per cent of the land surface to maquis (scrub) on ultrabasic massifs covered with ferruginous lateritic soils and on micaschist and chert outcrops with acidic soils. These soils are poor in lime, potash, and phosphates; on ultrabasic massifs they are locally rich in nickel, cobalt, and chromium compounds. Such soils set edaphic limits to tree growth, notably on high plateaux such as the Dôme de Tiébaghi in the north and in interior basins such as the Plaine des Lacs in the south. West of the ranges the drier foothills probably sustained woodland communities, grading into savanna and shrubland on the coastal plains.

Of botanical interest because of the numerous endemic species as well as those with Australian and Melanesian affinities, the existing vegetation has been profoundly modified by human activities (plate 1). Extensive areas were cleared and burned by Melanesian farmers, whose cultivation terraces are widespread, especially in the foothills west of the main ranges. There was further clearing and burning as well as the introduction of grazing animals and the development of mining activities after the arrival of the first settlers in the 1860s. The outcome is that forests now occupy only about 18 per cent of the land surface of New Caledonia, persisting mainly in the uplands, including the higher parts of some of the river valleys. Large areas that formerly carried forest or woodland have been converted to savanna dominated by swamp paper-bark trees known as niaouli (*Melaleuca quinquenervia*) or by mimosa (*Leucaena leucocephala*), gaiac (*Acacia spirorbis*), or lantana (*Lantana camara*) scrub, or to open grassland, by repeated burning and by stock grazing.

PLATE 1. A Relict Stand of Native Vegetation, Including *Araucaria* Spp., on an Unmined Sector of the Mé Aiu Plateau West of Canala. Such vegetation, rich in endemic species, was formerly extensive on the laterite cappings of ultrabasic massifs, but has been much reduced in extent by nickel mining.

Moreover, opencast mining of nickel and iron ores on hill crests and plateaux has inevitably resulted in destruction of the vegetation cover, not only in the quarried areas but also on surrounding hill slopes mantled by quarry waste and downwash (plate 2), and on the floors of neighbouring valleys (Jaffré et al. 1977). In addition, the existing vegetation cover has been extensively disrupted by landslides, gulleying, and associated fan deposition in areas where erosion was initiated or accelerated by such activities as road-making (plate 3), mineral prospecting, and the depletion of natural vegetation by clearing, grazing, and burning.

It is possible that some of the hill-slope erosion so widely evident in New Caledonia is the outcome of natural geomorphological processes, especially in the Massif du Sud and in the northwest, where the climate is relatively dry and tropical cyclones have generated torrential runoff and locally severe erosion at infrequent intervals, and on some steep slopes on deeply weathered formations. But the onset of widespread erosion during the past century and a half has been largely the outcome of human activities in an environment where the relative stability of steep hillsides mantled by deep weathering materials evidently depended on the persistence of a retentive natural vegetation (cf. Iltis 1979).

An assessment of the direct and indirect effects

PLATE 2. Downwashed and Slumped Waste from a Hilltop Nickel Mine Feeding Sand, Gravel, and Boulders into a Tributary of the Népoui River

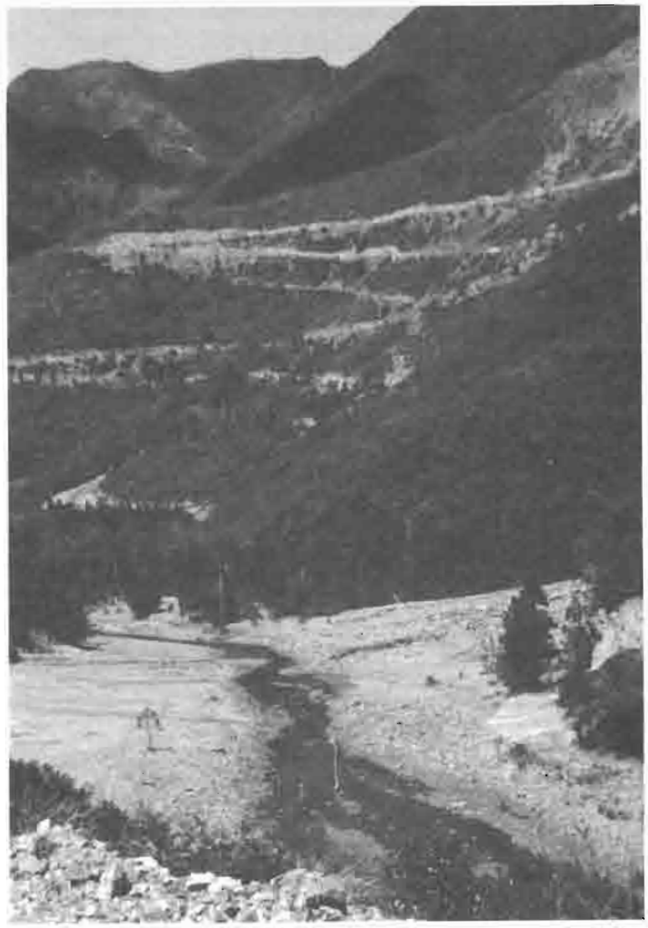

PLATE 3. Access Roads to Mining Areas are Prominent on Hillsides in the Ultrabasic Massifs of New Caledonia, and in Some Cases Roadworks Have Contributed to Slope Erosion. This example is in the Népoui valley, on the west coast of New Caledonia.

of opencast mining and other activities on the landscapes of New Caledonia, and in particular on river mouths and coastal systems, is best preceded by an account of the evolution of these landforms.

Landform Evolution

New Caledonia is geologically complex (Paris 1981), with areas of strongly folded sedimentary and metamorphic rocks and massifs of ultrabasic formations, mainly peridotites and serpentines, with overlying gabbros and intrusions of granodiorite in the southern regions. In addition, there are dissected hilly areas of Tertiary basalt, and extensive Quaternary piedmont fans and alluvial deposits, especially on the west coast, which has a lowland fringe of variable width in contrast with the generally steep east coast.

Evolution of the landforms of New Caledonia has been related partly to geological structure and component formations, and partly to a historical sequence of tectonic movements as well as climatic and sea-level fluctuations (Iltis 1981). Figure 1 shows the pattern of mountain relief, hill relief, depositional landforms, and coral reefs that make up New Caledonia. The basement rocks, which outcrop in the central and northern highlands, are mainly Palaeozoic schists, Mesozoic sandstones, greywackes, and limestones; they were uplifted, folded, and faulted by Lower Cretaceous earth movements, then deeply dissected by erosion. They were overlaid during Eocene times by ultrabasic formations, the origin and emplacement of which are still not fully understood. It is now widely thought that they originated as crustal material on the ocean floor and were pushed up and over the basement rocks by overthrusting due to collision of the Indo-Australian and Pacific plates; such overthrust rock masses are known as "nappes." Basalts which form hilly country between Bourail and Koumac on the west coast were evidently extruded in Eocene times as this overthrusting took place. The ultrabasic formations were then disrupted by a network of faulting due to revived tectonic movements. They have subsequently been deeply weathered and dissected by river valley incision, largely guided by the fault pattern, leaving residual steep-sided massifs. The resulting distribution of ultrabasic formations is shown in figure 3.

Ultrabasic rocks are ferromagnesian silicates, often with associated metallic compounds, which originally formed deep in the earth's crust. They include peridotites, which are olivine-rich nonfelspathic rocks, often modified into serpentine, a hydrated magnesium silicate, by processes of metamorphism due to intense heat or pressure. In New Caledonia these formations, emplaced by overthrusting, have persisted as upland areas. Since Oligocene times the uplands of New Caledonia have remained above sea level, and the ul-

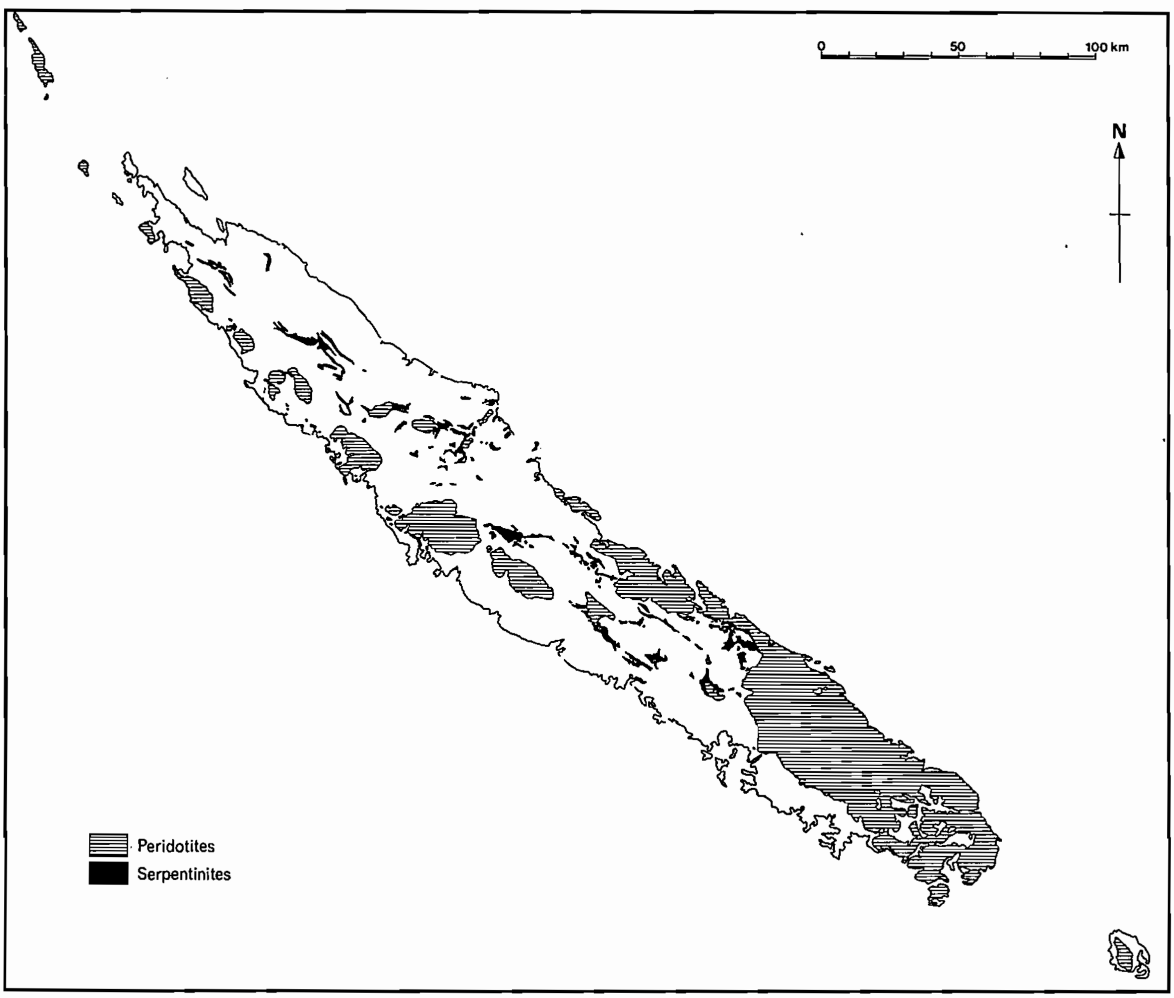

FIG. 3. Peridotites and Associated Formations in New Caledonia (from Atlas of New Caledonia)

trabasic rocks show subaerial weathering to depths of 20 to 30 metres with the formation of thick lateritic profiles in which are found the nickel, chromium, cobalt, and iron ores that have been widely mined. The plateaux which cap these massifs at various levels between 500 and 1,600 metres above sea level show peridotitic karst features, including enclosed depressions (pseudo-dolines) formed by the leaching of magnesium silicate beneath a porous ironstone duricrust (Wirthmann 1970). This ferruginous duricrust (50 to 80 per cent iron hydroxides) is often several metres thick, and rainfall percolating rapidly through it is responsible for solution and karst development. These features are well displayed in the lowland region of the Plaine des Lacs in southern New Caledonia, where solutional lowering of the land surface within fault-bounded depressions has produced almost enclosed basins that resemble limestone poljes.

Stages in the denudation of the New Caledonian highlands are marked by successive partial planation surfaces formed during episodes of stability in Tertiary times. Prolonged subaerial denudation during the Quaternary has led to the deposition of extensive terraces and colluvial piedmont fans in front of steep slopes, particularly in regions inland from the west coast of New Caledonia. The sequence of sediments deposited in these piedmonts indicates alternations of relatively rapid slope wastage, when torrential streams washed down broad fans of relatively coarse material ranging from sand gravel to cobbles and boulders, and episodes of gentler activity, when downwashed sediment was mainly sand, silt, and clay and weathering profiles developed on relatively stable depositional surfaces on the piedmont fans, with some subsurface accumulation of salts precipitated from groundwater, notably gypsum (calcium sulphate) and magnesium compounds. Phases of relatively rapid erosion in the uplands may have been initiated by tectonic uplift, but in general these alternations seem to have been mainly the outcome of climatic fluctuations. The most intensive erosion occurred as the result of increased runoff, either in periods of higher annual rainfall or, more probably, in brief episodes of torrential discharge in a more arid environment, where the vegetation cover was sparser, and soils and surface weathered materials more readily eroded. The intervening quieter episodes imply a gentler runoff, probably with a more luxuriant vegetation, sufficient to impede rainfall and runoff, and retain the soil and weathering mantle on all but the steepest slopes.

It is likely that under natural conditions (i.e., without any modification of the land surface and vegetation cover by human activity) these piedmont fans would have remained relatively stable in the present climatic environment. Runoff from forested uplands would now be carrying only small quantities of relatively fine-grained sediment down the narrow watercourses across the piedmont fans and into the sea. Such features are still seen locally on west coast piedmont fans, where the upper catchments of streams remain undisturbed by mining activities and fairly well vegetated, and it is these watercourses that provide a standard of reference against which the widespread modifications of channel form and sediment yield in recent decades can be gauged.

Coastal Features

The coastline of New Caledonia has small tide ranges, generally less than a metre, and wave action related to local, mainly easterly or south-easterly trade winds in coastal waters protected by extensive reef formations (Bird and Iltis 1983). It is dominated by features produced by submergence during the Holocene marine transgression, the last of a series of major sea-level oscillations that took place in the world's oceans during Quaternary times. Each time the sea level fell, New Caledonia was enlarged by the emergence of bordering sea floor areas; rivers extended their courses seaward and incised their valleys towards the lowered base levels (Launay 1972); coral reefs were exposed as limestone ridges subject to karstic dissection of the kind that is now seen on the uplifted atolls of Lifou and Maré in the Loyalty Isles to the north (Davis 1925). When the sea level rose, these features were submerged; some higher areas persisted as promontories and offshore islands, while intervening lowlands became embayments (e.g., the Baie de St. Vincent on the west coast) and the mouths of incised valleys became rias (e.g., the Baie de Prony in the far south and the fault-bounded Baie de Canala on the east coast) or estuarine inlets (e.g., the Nimbaye estuary at Ponérihouen and several other river mouths on the east coast). Some of these drained areas have subsequently been infilled with sediment to form deltaic plains and protruding deltas, especially on the west coast (e.g., the Dumbéa, Ouenghi, Iouanga, and Koumac deltas), but also on the southern half of the east coast (e.g., the Kouakoué, Ni, Ngoye, Comboui, Thio, Nakéty, Canala, Kouaoua, Koua, and Houaïlou-Néaoua deltas). As a generalization, rivers that drain catchments which include deeply weathered ultrabasic formations had built deltas, whereas those draining Mesozoic and Tertiary sedimentary and volcanic regions, where the weathered mantle is relatively thin, flowed into estuarine mouths or rias, indicating a natural contrast in the regional sediment-yield regime, based on geological features, prior to any impact of mining activities. As will be seen, human activities have accelerated sediment yields in many areas, but the acceleration has been much more emphatic where the highly erodible weathered mantles of ultrabasic massifs have been disturbed by opencast nickel and iron ore extraction, augmenting sediment yields to rivers and their deltas.

The Holocene sea-level rise has been followed by revival and renewed growth of coralline barrier and patch reefs offshore, thereby augmenting structures that had been developing intermittently through Pleistocene times, and the initiation of Holocene fringing reefs along the present coastline (Chevalier 1973). However, the south-east coast near Yaté is bordered by an emerged Pleistocene fringing reef up to 10 metres above sea level, and similar emerged reefs up to 20 metres above sea level encircle the Ile des Pins to the south. According to Launay (1982), these fringing reefs originated during interglacial phases of the late Pleistocene when the sea stood close to its present level, and have been raised to their present positions by subsequent tectonic movements; the reefs on the Ile des Pins have been dated at 120,000, 165,000, and more than 200,000 years B.P. by isotopic analyses (Launay 1982). It is thus evident that the south-east coast and the adjacent Ile des Pins have had a different tectonic history from the rest of New Caledonia, subsiding during the phase of general Neogene uplift and emerging during the phase of general Late Quaternary subsidence.

Much of the east coast is steep, particularly where there are fault scarps 300 to 400 metres high bounding the ultrabasic massifs, which descend abruptly to the sea with gradients of more than 50 degrees. Basal marine cliffing is limited, except on a few promontories exposed to stronger oceanic waves entering through gaps in the barrier reefs (e.g., on the seaward flank of Cap Bocage). The boldest cliffs, up to 40 metres high, are on Cap Ndoua in the far south, where a broad gap in the outlying reefs permits the prevailing south-easterly ocean waves to reach the coastline. The steep coasts bordering the ultrabasic massifs are interrupted by inlets and branching rias at the mouths of river valleys between Yaté and Ponérihouen. Some of the valley mouths have deltaic features produced by fluvial deposition (e.g., Thio) or spits and beach ridges where wave action has reworked fluvially supplied sands and gravels (e.g., Kouaoua). Further north a sector of hilly coastal country on strongly folded Mesozoic sandstones and volcanic rocks has gentler coastal slopes bordered by a low depositional terrace with fringing coral reefs, prominent on the Cap Bayes peninsula and in the Touho district. Beaches of coralline sand and gravel extend along the reef-fringed coastline, and beaches of fluvial sand and gravel occur near river mouths. The rivers widen to estuaries fringed by mangroves, and their mouths are often encumbered by sandy spits that have locally been prograded as beach-ridge plains (e.g., Nimbaye, Tchamba, Amoa, Tiwaka). The adjacent sea floor is also dominated by terrigenous sediments, mainly silt and clay washed into the sea by rivers draining a steep and rainy hinterland; but further out, towards the barrier reefs, calcareous coralline sediments prevail (Guilcher 1963). To the north, alignments of steep-sided karstic pinnacles and towers of Eocene limestone, with basal notches and caves cut by marine erosion, distinguish the Hienghène coast, where rivers enter the sea by way of deep winding rias formed by the Holocene marine submergence of previously incised river valleys. North of Hienghène the coast is again steep along the flanks of the metamorphic Panié massif, a high range of metamorphic rocks. Bold spurs are separated by deep valleys, several of which have spectacular waterfalls where streams flow across massive rock outcrops. The spurs have been truncated by steep coastal slopes, undercut at the base by active cliffs a few metres high, especially near Ouaième where a broad gap in the barrier reefs allows stronger oceanic waves to reach the coastline. Further north the Massif du Panié declines, and its seaward slopes are bordered by a coastal plain between Pouébo and Balade, a depositional lowland partly covered by mangrove forests that are protected from the open sea by fringing and barrier reefs. The ranges then decline further through the Pam peninsula, their trend being continued by the outlying high island of Balabio. Fringing and nearshore reefs, and shoals in the lee of the barrier reef (Récif de Cook) are extensively exposed at low tide.

In northern New Caledonia, the country's longest river, the Diahot (length: 90 km), flows into a gulf that occupies a structural trough between the Balabio and Arama ranges. Wide swampy plains have been built by deltaic deposition from the Diahot, which has extended its levees of silt and sand seaward in such a way as to enclose depressions occupied by extensive mangroves backed by salt pans that are subject to intensive evaporation in the long dry season. Associated depositional features extend along the eastern shores of the Arama peninsula, which gradually declines and narrows to Pointe Narian. Ile Baaba (mainly sedimentary) and the Iles Belep (entirely of ultrabasic rocks) are outlying high islands in the same structural alignment.

In spite of the proximity of steep-sided ultrabasic massifs, the northern half of the west coast of New Caledonia is low-lying, consisting of gently sloping Pleistocene piedmont fans that have been partially submerged by the sea, and alluvial valley floors built by fluvial deposition. Rivers such as the Néhoué and the Poya have built intricate mangrove-fringed deltas bordered by tidal mudflats, and mangroves also occur in sheltered inlets and embayments, in the lee of headlands and offshore islands, and alongside estuaries and shallow lagoons down the west coast. About 20 species of mangroves are present in New Caledonia, but *Rhizophora* and *Avicennia* are the most common on this coast, with large stands near Poum and in the Baie de Néhoué. Behind the mangroves there are sparse salt marshes and extensive unvegetated salt pans, submerged only at the highest tides or after widespread river flooding and dessicated during the dry season that here extends from April to December. Beaches occur intermittently, some consisting mainly of coral sand derived from nearby reefs, others of fluvial sand and gravel or material washed out of the piedmont deposits. The diversity of coastal sediments around New Caledonia is due partly to geological variety in the hinterland, partly to intricacy of coastal configuration, and partly to the sheltering effects of the surrounding reefs, which generally exclude strong wave action and have prevented shoreward drifting of sea floor sediments (cf. Bird 1972).

The Koumac River has delivered substantial quantities of chert (phthanite) gravel, derived from Cenozoic outcrops and Pleistocene terraces and piedmont fans in its upper catchment, to its deltaic coastline, and beaches and spits of this material have grown northwards from there in response to longshore drifting by the prevailing southerly waves in coastal waters. By contrast, the Néra delta has a gently-curving sandy shoreline behind the Baie de Gouaro, shaped by ocean swell arriving through a broad gap in the barrier reefs.

Further south the hinterland becomes hilly, and some higher areas run out as promontories, such as the limestone plateaux of the Muéo and Népoui peninsulas, separated by shoaly bays into which rivers are carrying sediments and protected to seaward by coral reef formations. South of Bourail the promontories become more numerous (Mara, Lebris, Ouano, Bouraké), and there is local cliffing on sectors exposed to stormy wave action, especially when there are gaps in the barrier reef, as at Roche Percée near Gouaro. Broad intervening bays have wide intertidal zones occupied by extensive mangroves and salt marshes, as at Mara (Baltzer 1965). Some of these are threaded by wave-built cheniers of sandy material. The Baie de St. Vincent has been formed by marine submergence of an undulating plain, the higher parts of which persist as promontories and hilly islands; it is well protected by outlying barrier reefs, and marine cliffing is limited to small sectors on the seaward margins of steep-sided promontories and islands. The Ouaméni, Ouenghi, and Tontouta rivers are building mangrove-fringed deltas into bordering embayments, and mangroves are also present on the lee shores of some of the islands; but comparison of outlines shown on Banare's chart of the Baie de St. Vincent, made in 1863, with modern air photographs (1954, 1976) shows only minor changes in coastal features, chiefly around the river mouths. Beaches of fluvially supplied sand occur locally, as do beaches of cliff-derived material and, adjacent to reef areas, coralline sands. Bay-floor sediments show related patterns of terrigenous and reefal material (Dugas 1974). On some of the outer islands there are deposits of Pleistocene dune calcarenite, formed from wind-blown calcareous sands that accumulated during the late Pleistocene low-sea-level phase, when the climate was drier than it is now (Coudray 1976). Dunes are otherwise very rare in New Caledonia.

South from the Baie de St. Vincent the coast is generally hilly and indented by bays and inlets, notably the intricate Baie de Dumbéa, which is flanked by long narrow peninsulas, the delta of the Dumbéa River developing at its head. Here Baltzer (1969) has identified zonations of mangrove and salt marsh vegetation related to the depth and duration of intertidal submergence (see fig. 19). The hilly Nouméa peninsula is reef-fringed, its outer embayments having sandy beaches of tourist importance culminating in the cuspate foreland south of the Anse Vata, while the inner embayments, more sheltered, have sectors of mangrove shore. Beyond the Baie de Boulari rise the steep slopes of Mont Dore, an outlier of ultrabasic rocks associated with the Grand Massif du Sud. This marks the commencement of bolder coasts, with valley-mouth inlets (Rivière de Pirogues) and branching rias (Baie de Prony). Ile Ouen is a steep-sided high island, also of ultrabasic rock, beyond which the barrier reefs (Grand Récif du Sud) loop seawards to enclose a sea area dotted by patch reefs, some of which carry low sandy cays (Guilcher 1965). As has been noted, the cliffed coast of Cap Ndoua faces deeper and stormier seas, but to the east a chain of reefs with intervening deep channels extends to the Ile des Pins, where emerged fringing reefs form a lowland encircling the hilly area of Pic Nga, another outlier of ultrabasic rocks.

2. THE HISTORY AND ECONOMICS OF MINING IN NEW CALEDONIA

The mineral resources of New Caledonia have been the basis of the Territory's economy. In the past few decades, mining has generated more than 90 per cent of exports from New Caledonia, its value far exceeding the production from agriculture, forestry, fisheries, and tourism. For more than a century, since the beginnings of colonization, there has been mining of metallic mineral ores, notably of nickel, cobalt, chromium, iron, copper, lead, zinc, gold, silver, manganese, and antimony. In addition, deposits of coal, gypsum, giobertite (magnesium carbonate), and phosphate have been mined.

Much of this mineral exploitation has been very localized, and many of the mines have now been long abandoned; they have left almost no impact on the landscape of New Caledonia. This was particularly the case with the copper, lead, and zinc mines in the north (in the region of Ouégoa), which were worked by shafts and adits (hillside tunnels) rather than opencast pits, and only intermittently. They closed before 1930. Cobalt was also mined in this way. It was found to be associated with nickel ores in the form of asbolane concretions with a mean cobalt content of about 5 per cent. Mining operations were artisanal, many small exploratory excavations seeking and following these concretions through adits cut into the laterites. Between 1890 and 1910 New Caledonia was the world's leading producer of cobalt, but in 1927 production ceased. By then about 100,000 tonnes of cobalt ore had been exported.

The existence of coal deposits in rocks of Senonien age was known from the early years of colonization, but the only significant mining of these deposits took place near Moindou on the west coast between 1924 and 1930. Underground coal mining had very little impact on the landscape, but some 77,000 tonnes of coal were produced during this period and used in nickel smelting. However, by 1930 it had become clear that, because of the poor quality of this coal and the high cost of its extraction, it could not compete with imported Australian coke, and coal mining in New Caledonia was abandoned. Gypsum and giobertite were also used in nickel metallurgy, the first as a sulphurant, the second as a smelter. Small lenticular deposits of gypsum found in old marine or lagoon shore deposits along the west coast were mined between 1917 and 1954, yielding 320,000 tonnes. Giobertite is derived from the weathering of peridotites, and was mined sporadically from several small concentrations at the foot of the massifs along the west coast. This mining ceased in 1970.

Apart from these mineral resources, there are four metallic ores the opencast mining of which has had an impact on the landscape of New Caledonia. Nickel is the most important of these and is still basic to the Territory's economy, but there has also been mining of chromium, iron, and to a lesser extent manganese.

Nickel

Discovered in 1864 by the engineer Jules Garnier, nickel oxide occurs as an ore named garnierite, resulting from the weathering of peridotites in the ultrabasic massifs which cover about a third of the land surface of the main island of New Caledonia. Nickel has concentrations of 0.2 to 0.3 per cent in the original peridotite. It is liberated by hydrolysis of nickel-bearing silicates, and becomes concentrated towards the base of the weathering profile, where it can attain exploitable concentrations of 2 to 5 per cent (fig. 4). At the weathering front, adjacent to the bedrock and in rock fissures, the nickel content locally attains 10 to 15 per cent in

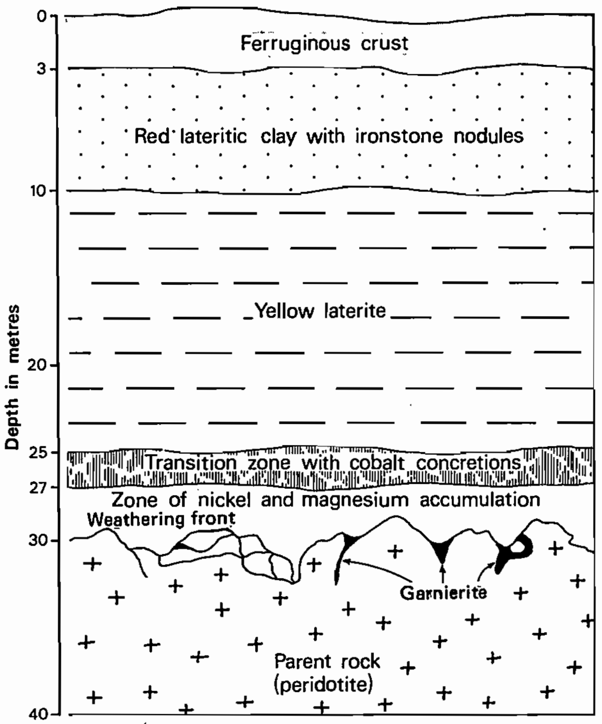

FIG. 4. Weathering Profile Characteristic of Hilltop Plateaux on Ultrabasic Massifs in New Caledonia. Shown are the typical locations of nickel ore (garnierite) at the weathering front, and zones of nickel, chromite, and cobalt accumulation beneath the red and yellow laterite horizons and the ferruginous crust. (After Paris 1981.)

the form of green garnierite, but this very rich ore is present only in small quantities. This was the ore originally mined under artisanal conditions. Modern mechanized methods can utilize less rich ores. At present, the mean concentration of mined nickel ore is about 2.6 per cent, and reserves with at least this concentration are estimated at 200 million tonnes. However, the superficial laterites also contain nickel ore of lower concentration (1.3 to 1.6 per cent), as yet unexploited, but representing enormous reserves for the future. It has been calculated that New Caledonia contains 40 per cent of the known nickel ore resources in the world.

Mining of nickel began in 1875 in the Houaïlou and Canala regions. By the end of 1981, just over a century of mining had yielded 110 million tonnes of nickel ore, equivalent to 2.5 million tonnes of pure nickel. About half of the nickel ore production has been smelted in New Caledonia, the other half being exported, mainly to Japan.

In the early stages, nickel ore was mined by hand in tunnels or trenches which followed the richest seams. Mining has subsequently become open-cast, with increasing mechanization. At present, the nickel ore is quarried by powerful mechanical shovels which cut into cliffs five to eight metres high (plates 4 and 5). After sorting, the ore is taken down to coastal wharfs in large lorries, or on conveyor belts which have been built from the more important mining centres. This kind of mining necessitates the removal of huge masses of overburden: it is estimated that an average of five tonnes of rocky material must be removed to obtain one tonne of nickel ore. As a result, vast amounts of earthy waste material have been displaced in the course of nickel mining.

Figure 5 shows the evolution of nickel ore production from 1890 to 1981, and also the accompanying diminution in the nickel content of extracted ore (given as percentage of metal in dried ore, the natural ore containing an average of 25 per cent moisture). Before 1890, nickel ore production was very slight and was poorly recorded, but thereafter, as the graph shows, it increased until the First World War, fell back between 1917 and 1925, then revived in the next 15 years to attain nearly 500,000 tonnes in 1940. After a long period of depression in the 1940s, it began to grow strongly, reaching a million tonnes in 1955. Except for setbacks in 1958 and 1962, expansion continued, attaining a record yield of nearly 8 million tonnes in 1971. Figure 6 shows areas where mining has occurred.

Since 1971 there has been a decline, related to the world economic recession which reduced prices and lowered demand for nickel, and to competition from other nickel-ore-producing countries, notably Indonesia and the Philippines. In spite of a small recovery in 1974–1975, nickel ore production has continued to decline. In 1981 it was less than 4 million tonnes.

Under the legal system operating in the Territory of New Caledonia, mining titles (concessions and exploitation permits) issued for the mining of nickel and associated mineral ores cover 380,000 hectares, about 22 per cent of the surface of the main island of New Caledonia. The bulk of the mining area is shared between eight leading companies, of which the Société Le Nickel (SLN) is the largest, with 175,000 hectares of

PLATE 4. Quarrying for Nickel Ore on the Thio Plateau, Showing Terraced Forms Produced by Excavation at Successively Lower Levels

PLATE 5. Quarry on the Thio Plateau, Showing Zone of Green Garnierite (arrowed)

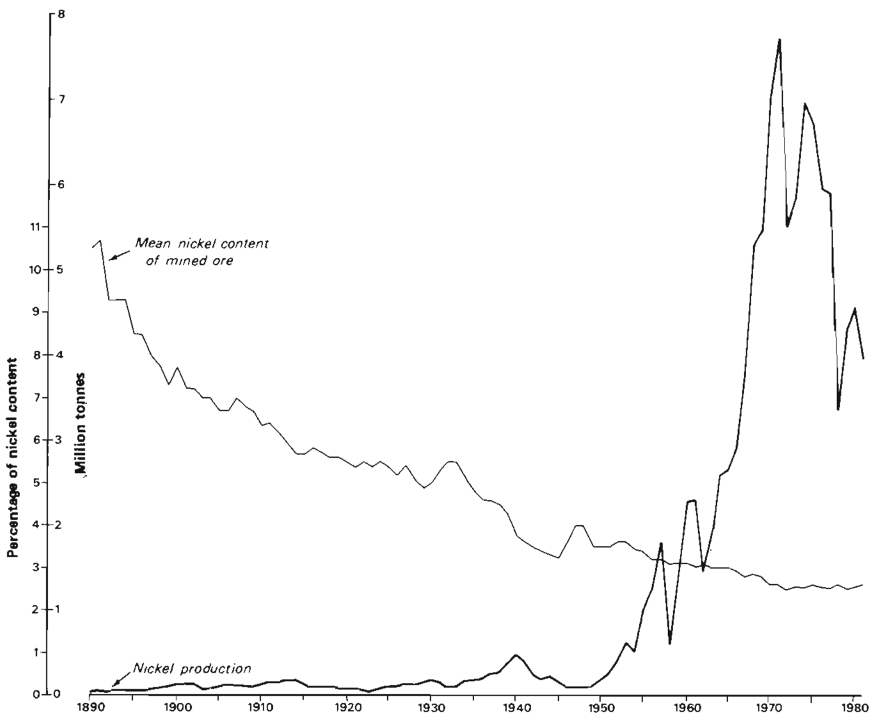

FIG. 5. Development of Nickel Production in New Caledonia 1890 to 1981 and Mean Nickel Content of Mined Ore during That Period

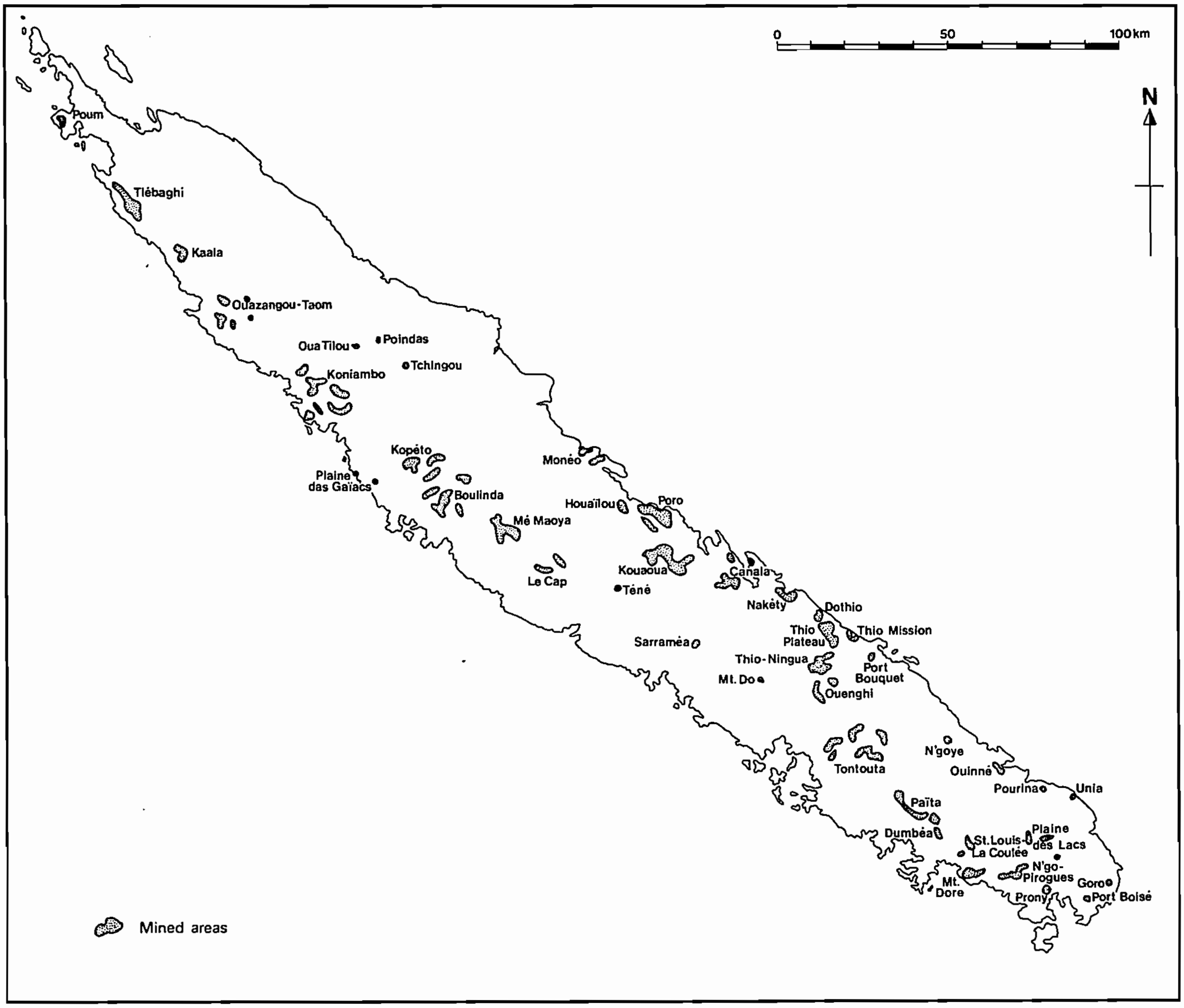

FIG. 6. Main Areas Where Mining Has Taken Place in New Caledonia

concessions. The exploited areas have varied considerably. From 21,500 hectares in 1971, the year of maximum production, they have fallen to 8,700 in 1981.

Figure 7 shows the distribution of about 330 opencast nickel mines, based on information from the 1:200,000 geological map (Paris 1981). The most important mines (i.e., those that have yielded more than 15,000 tonnes) are represented by large dots on this map. They can be grouped within about 40 centres of exploitation, generally corresponding with the distribution of ultrabasic massifs, and it is in terms of these that production figures are available for 1971 and 1981 (figs. 8 and 9).

Four major mining centres have produced 62 per cent of the nickel ore so far extracted. These are Thio, Kouaoua, and Poro on the east coast and Népoui-Kopeto on the west coast. Mined continuously since the end of the nineteenth century, the deposits of the Plateau de Thio have yielded 17 per cent of the total nickel ore production from New Caledonia, and with the adjacent Thio-Mission, Ningua, and Ouenghi mines, this region has produced 24 per cent of the nickel ore so far won from New Caledonia. Further north the long-exploited mining area of Kouaoua lies in second position with 14 per cent, and the more recently developed centres of Poro and Népoui, developed largely during the "nickel boom" of 1968–1973, have yielded 12 per cent each.

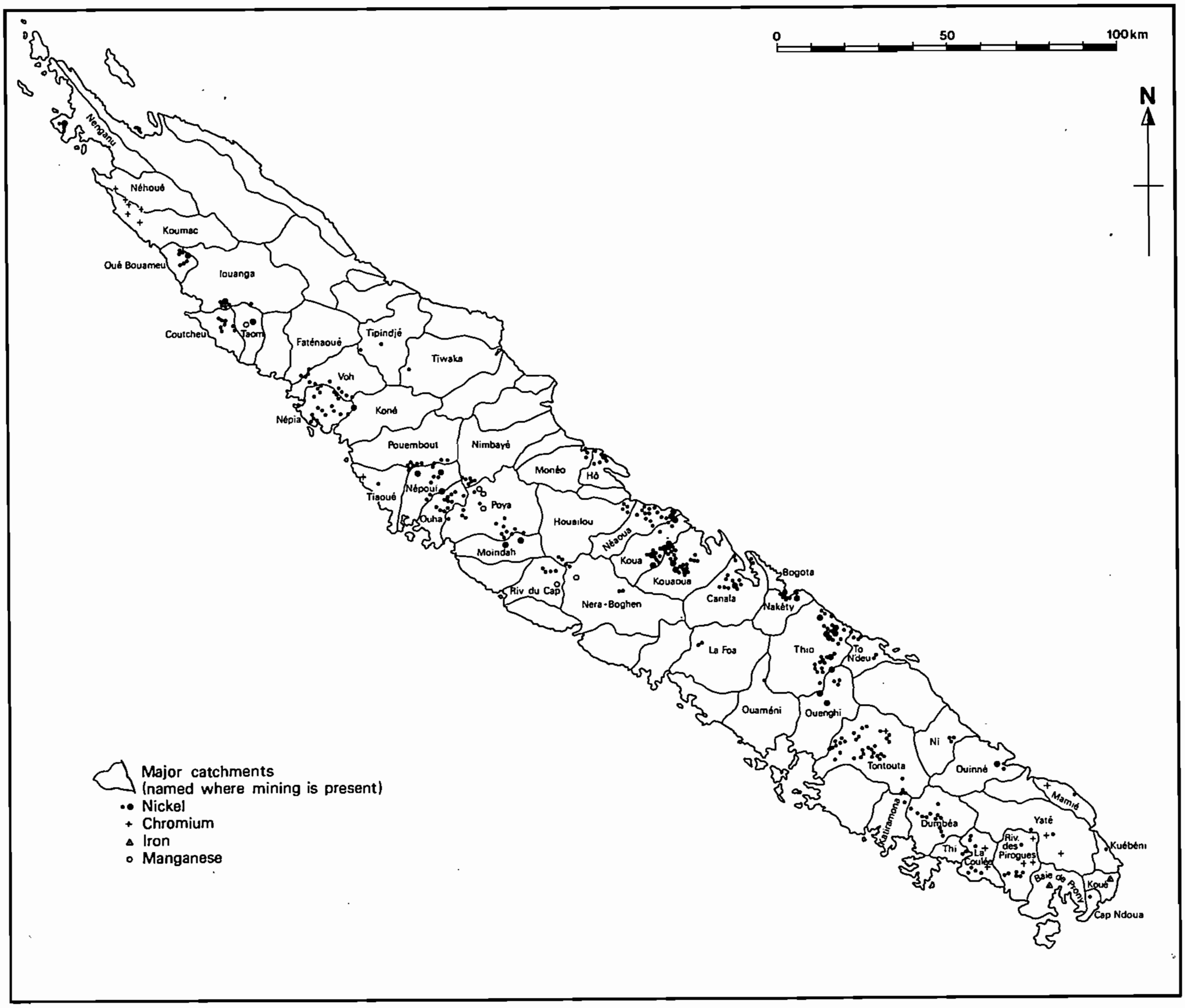

FIG. 7. Locations of Nickel, Chromium, Iron, and Manganese Mining in New Caledonia up to 1981

The rest of the nickel ore production has come from a large number of smaller mines, most of which have been worked only sporadically. The most notable, yielding between 2 and 5 per cent of the New Caledonian nickel ore production, have been Ouazangou-Taom, Tontouta, Kaala, Mé Maoya, and Koniambo on the west coast, and Nakéty, Canala, Monéo, and Ouinné on the east coast. The Massif de Koniambo was mined until about 1950, and in some years was more productive than the Thio mines. However, in 1950 the Massif de Koniambo mining halted, and this region was placed in reserve. It still contains the largest reserves of rich nickel ore (garnierite) in New Caledonia. Small mining centres in the south, such as Paita, Dumbéa, St. Louis, and Mont Dore have been exploited intermittently, but have nevertheless yielded some 3.5 per cent of total nickel ore production.

Figures 8 and 9 show the distribution of nickel ore producing centres in 1971 (total production 7,720,000 tonnes) and in 1981 (3,980,000 tonnes). In the course of this decade of diminishing mining activity, many small mines worked chiefly to produce nickel ore for export to Japan were closed down, and production became concentrated at the four major mining centres, mainly supplying the SLN factory in Nouméa with ore for processing. The contribution from these four mining centres increased from 53 per cent of the New Caledonian nickel ore pro-

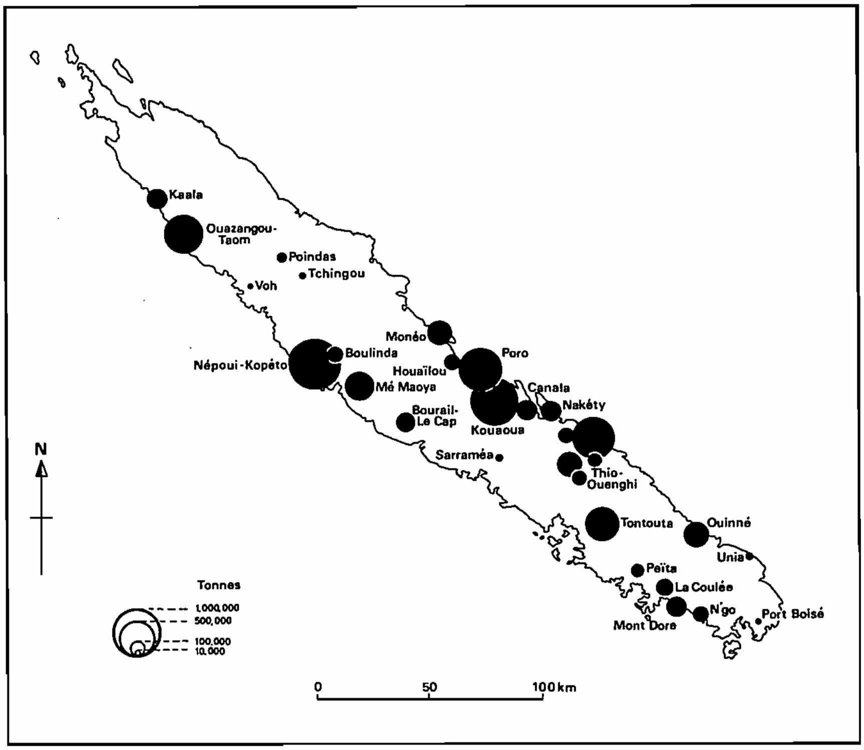

FIG. 8. Nickel Ore Production in New Caledonia in 1971 (total production 7,720,000 tonnes)

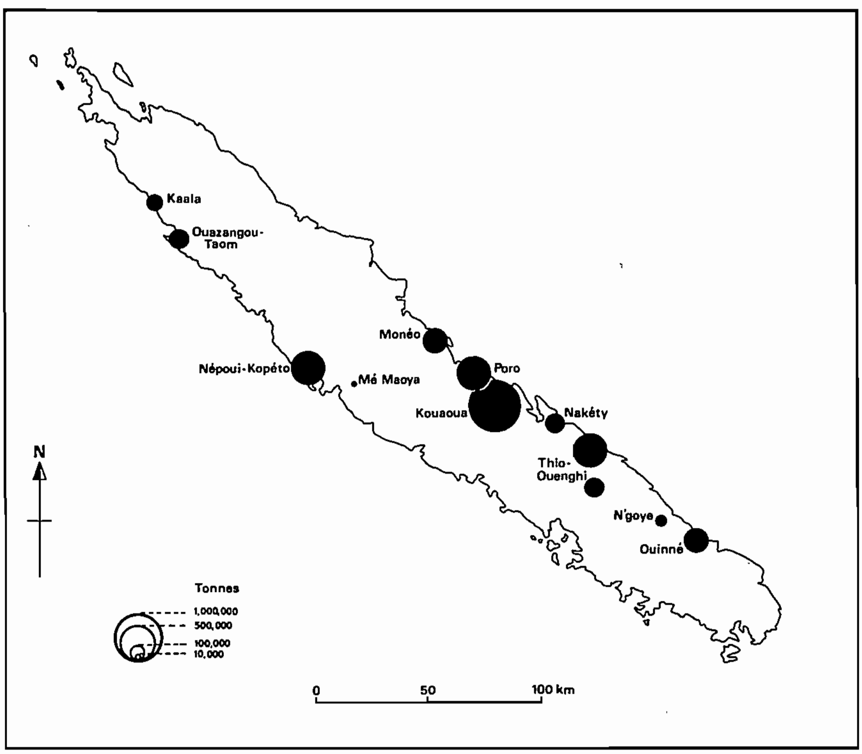

FIG. 9. Nickel Ore Production in New Caledonia in 1981 (total production 3,980,000 tonnes)

duction in 1971 to 72 per cent in 1981, although their actual yield fell from more than 4 million tonnes to less than 3 million tonnes over this period. Kouaoua has now become the principal mining centre, ahead of Thio, Poro, and Népoui. In all, 132 mines were active in 1971, but only 31 in 1981.

During 1982 the economic situation worsened. The important Ouinné mine ceased activity at the end of the year, and the reduction in demand for nickel led SLN to announce that the Népoui and Poro mining centres would close down in 1983.

Yet, as will be shown in later chapters, the problem of landscape impact of the vast quantities of waste material that has resulted from all this mining activity will not be reduced simply because of the downturn in the economy and the closure of so many nickel mines. This impact is as conspicuous now in the many areas where mining came to an end during the past decade as in the few areas where nickel ore is still being extracted.

Chromium

Like nickel ore, the chromium ores are associated with the ultrabasic rocks, but their extraction has had much less impact on the landscape because the richest ores are localized and mining has been generally by way of shafts and adits, with only a few opencast workings. The chromium ores occur in two forms: primary chromite in highly concentrated deposits containing at least 50 per cent chromium within the peridotites, and detrital chromite with a much lower chromium content (about 5 per cent) in the laterite capping and in derived fluvial or littoral deposits (chromium content up to 20 per cent).

Chromium ores were mined continuously from 1880 to 1962; production totalled 3,285,000 tonnes, with an average chromium metal content of 53 per cent (fig. 10). During this period chromium ore mining produced more metal than nickel ore mining. The bulk of the chromium ore came from the chromite deposits of Tiébaghi, in northern New Caledonia, which yielded 85 per cent of the total production. Extraction was by opencast mining on the Tiébaghi Plateau until 1930, then by underground mining until 1962, when the mines closed. Consequently, waste heaps from the mining of chromium ore are localized and of limited volume. The remaining 15 per cent of chromium ore production came from many small mines, chiefly in the Massif du Sud, where about 80 mines operated, although only a dozen yielded significant chromite production.

Since 1976 there has been a revival of interest in chromium mining in New Caledonia. Three small companies have reopened mines in the Massif du Sud, and a major project is in operation to extract chromite from the Tiébaghi massif by means of underground mining, with an expected production of 100,000 tonnes per year.

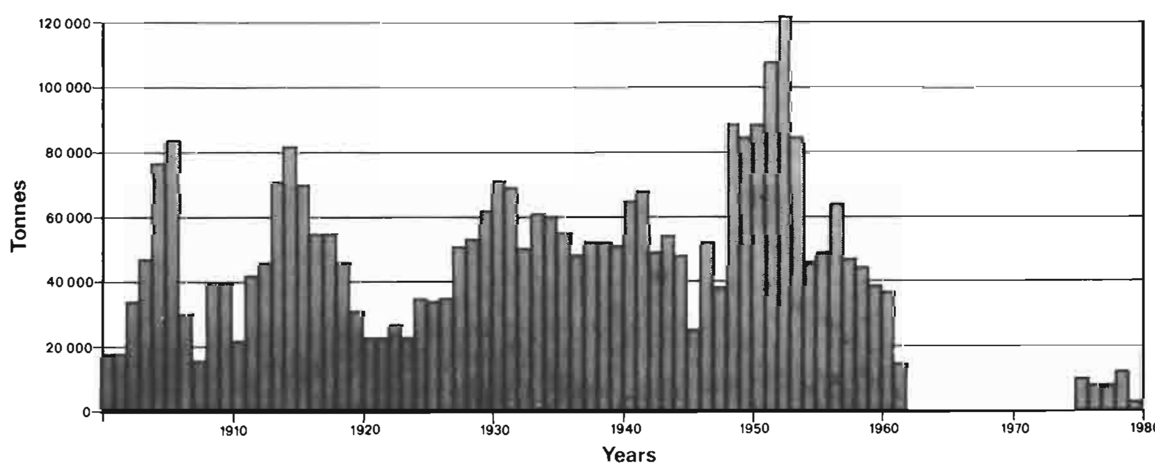

FIG. 10. Chromium Ore Production in New Caledonia, 1901–1980

Iron

The ferruginous laterites and crusts which cap weathered peridotites in the Massif du Sud contain important reserves of iron ore, but their high nickel, chromium, and aluminium content has impeded their exploitation. Nevertheless, these iron ores were mined by opencast methods near Goro between 1937 and 1941 (yielding 400,000 tonnes), and near the Baie de Prony between 1956 and 1968 (yielding 3 million tonnes). Readily accessible in the surface formations, where the iron content attains 55 to 58 per cent, this ore was exported to Japan and Australia. The impact on the landscape has been severe, for removal of ferruginous material has left extensive bare surfaces subject to sheet and gully erosion.

Manganese

Manganese ores are found associated with basaltic outcrops on the west coast of New Caledonia. Deposits located near Bourail, Poya, and Ouaco were quarried between 1918 and 1922 and again between 1949 and 1953, producing a total of about 60,000 tonnes of ore with an average content of 49 per cent manganese. The ores were exported, mainly to the United States. The landscape impacts of this mining have been negligible in comparison with those resulting from the extraction of nickel and iron ores.

The Mining Economy of New Caledonia

Metal Production

Nickel metallurgy has accompanied mining since its inception, the remoteness of European markets justifying the smelting of the ore within New Caledonia (Glasser 1904, Antheaume 1981). The first nickel smelter began operating at Pointe Chaleix, Nouméa, in 1879, and two other processing plants were subsequently established, one by the Société des Hauts-Fourneaux de Nouméa at Doniambo, Nouméa, in 1910, the other by SLN at Thio in 1913. The latter closed in 1931, when the nickel smelting plant at Doniambo passed into the control of SLN.

New Caledonian nickel is produced in two forms, as ferro-nickel alloys (22 to 37 per cent nickel content) which can be used directly in the production of special steels, and more concentrated ingots (75 to 78 per cent nickel), which are sent to Le Havre in France for refinement into purer metal.

Production capacity from Doniambo was doubled between 1970 and 1978 to attain 90,000 tonnes per year of nickel, about 10 per cent of the total nickel-producing capacity of Western countries. However, after growing rapidly to 71,000 tonnes in 1975, nickel production has been severely curtailed by the economic recession. In 1982 SLN produced only 35,000 tonnes of nickel, and production in 1983 is likely to be limited to 24,000 tonnes, just over a quarter of the capacity of the plant.

Employment

As a result of the closure of many nickel mines and reduced production, the number of people employed in nickel mining has declined during the past decade (see table 3). By the end of 1982 the number employed had fallen to 1,160. Employment in chromium mining now stands at 128.

The number employed in processing nickel ore at the Doniambo plant fell from 3,394 in 1971 to 2,274 in 1981. In all, employment in mining and metallurgy in New Caledonia has fallen by 42 per cent in this decade, the population of the Territory having grown about 30 per cent over the same period; in 1971 it accounted for 20 per cent of wage earners in New Caledonia, but in 1981 the proportion had fallen to 12 per cent. Société Le Nickel planned to reduce its workforce further during 1983.

Nickel Exports

Nickel ore and derived metallurgical products represent about 97 per cent of the total value of exports from New Caledonia (i.e., physical exports, excluding income from tourism). Such local products as coffee, copra, and troca furnish only 0.5 per cent of the value of the Territory's exports, the balance consisting mainly of imported items re-exported to other Pacific islands, notably Vanuatu, Wallis Island, and French Polynesia.

In 1979 New Caledonian nickel represented about 19 per cent of the total value of exports from the South Pacific region, less than the copper production from Papua New Guinea, which

TABLE 3. Number of People Employed in Nickel Mining in 1971 and 1981 and Percentage Change

	1971	1981	Change (%)
Société Le Nickel mines			
Thio	536	245	−54
Kouaoua	128	199	+55
Poro	239	173	−28
Népoui	304	211	−31
	1,207	828	−31
Small mining enterprises	1,041	340	−67
Contractors (haulage, lighterage)	950	248	−74
Total	3,198	1,416	−56

accounted for 23 per cent (Navunisaravi and Rakanace 1980).

Figure 11 shows the evolution of the value of exports of nickel ore and metallurgical products from 1971 to 1982. They attained 30 billion CFP francs in 1981 (about US$300 million), but in 1982 they had declined to 25 billion CFP francs (then equivalent to US$210 million). The proportion of nickel ore exported (entirely to Japan) fell from 35 per cent in 1971 to 15 to 20 per cent in the early 1980s.

Economic Imbalance

Imports to New Caledonia have grown considerably in recent years, and the declining value of nickel exports makes it difficult to offset the costs of imports. In the absence of substantial development in other sectors of the economy, New Caledonia is unable to maintain its standard of living without aid from France. By 1980 mining and metallurgy generated only 16 per cent of the gross domestic product of the Territory (compared with 25 to 30 per cent in the early 1970s),

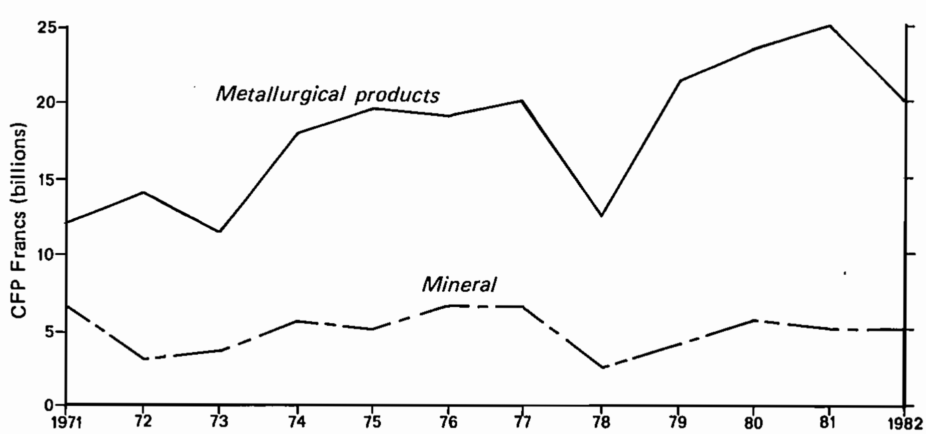

FIG. 11. Evolution of the Export Value of Mineral (nickel ore) and Metallurgical Products from New Caledonia, 1971–1982 (FOB value, actual prices)

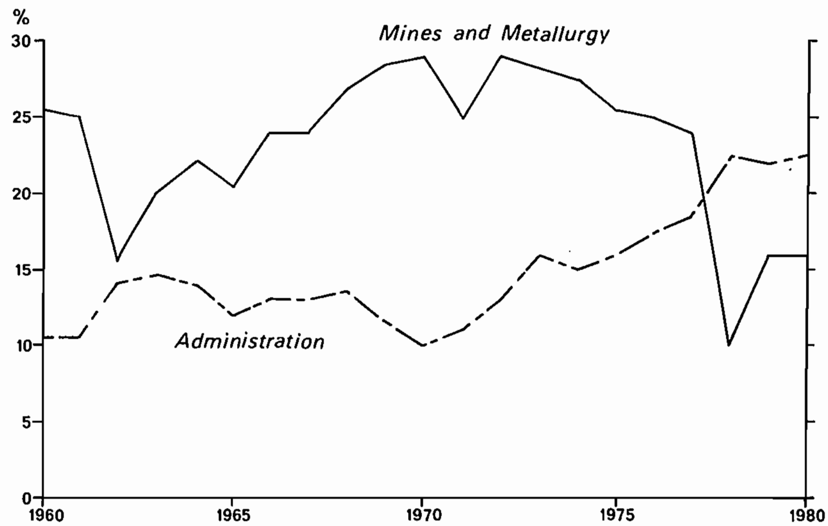

FIG. 12. Contributions of Mines and Metallurgy and of the Administration to the Economy of New Caledonia between 1960 and 1980 (expressed as percentage of gross domestic product)

while the contribution of the administration (i.e., the wages paid by it) was 23 per cent (fig. 12). Exports in the same year provided only 57 per cent of the total income of the Territory, the balance being supplied from France (Service de la Statistique 1980).

Implications

It will be evident from this review that mining, especially of nickel ores, has been vital to the development of the New Caledonian economy in its present form, and it is natural that the revival and further expansion of mining activity is seen as the best hope for the revival of the Territory's economy in the future. It is against this economic background, with its social and political undertones, that we turn to consider in more detail the landscape impacts and ecological consequences of the opencast mining that has occurred in the past century in New Caledonia.

3. THE IMPACTS OF OPENCAST MINING IN NEW CALEDONIA

During October 1982, surveys were carried out to assess the impacts of opencast mining on rivers and coastal systems in New Caledonia. Features shown on vertical air photographs taken by the Institut Géographique National in 1954–1955 (scale 1:40,000) were compared with those on air photographs taken in 1976 (scale 1:20,000), and with the present configuration examined in the field. In northern New Caledonia in 1982 many of the rivers still showed the effects of torrential runoff during Cyclone Gyan (24–25 December 1981), when large quantities of sediment of varying calibre were carried downstream. Severe flooding was recorded for the Diahot, Koumac, and Iouanga rivers in the north-west, and there was torrential flow down ungauged streams to the west coast between Voh and Koumac.

The problem of deciding how far opencast mining has influenced the form and sediment content of river channels and to what extent it has modified features at river mouths and in adjacent coastal and nearshore environments was considered on the basis of each of the major river systems draining to New Caledonia's western and eastern coastlines (fig. 2). These assessments are given below, taking the river systems in counterclockwise order from the north.

Diahot

Opening north-westward into the Baie d'Harcourt, the Diahot (catchment: 620 sq km) carries a substantial load of fine-grained sediment, mainly sand and silt, derived from the Mesozoic sedimentary formations of the Central Ranges and from the mica-schists of the Panié massif. Sediment delivered to the river mouth, mainly during flood episodes, has been built into channel-side levees prolonged as sedimentary jetties forming the framework of a delta that includes extensive mangrove swamps as well as dry saline plains. The rate of sediment yield may have been increased in historical times by the cutting and burning of forest and woodland vegetation and the introduction of grazing, resulting in accelerated soil erosion on friable materials.

Néhoué

This river system drains a basin of 229 sq km in north-western New Caledonia, its northern tributaries flowing from the schistose highlands of the Forêt d'Ougne Range, while the southern tributaries include streams flowing from the ultrabasic massif of Tiébaghi. This massif has been mined for chromium ore, at first opencast, then mainly in shafts and adits. The Néhoué and its tributaries have water stained red with ferruginous clay in suspension, and it is likely that their loads have been augmented by mining waste and material eroded from areas where the surface has been disturbed by prospecting. However, although some red mud has reached the deltaic region, features at the mouth of the Néhoué have so far been little modified by the effects of mining in the catchment.

Koumac

The Koumac and its tributaries drain an extensive catchment (area: 258 sq km) in northern New Caledonia, where the geological formations include schists, sandstones, limestones, and phthanite chert, a form of hard cryptocrystalline silicified sediment. This latter material has broken up into coarse gravels, present in the Pleistocene river terraces and piedmont fans bordering the upper valleys, and abundant in the river channel downstream past Koumac to the delta region. During episodes of flooding, gravel has been carried to the mouth of the river, and longshore drifting has thence swept it northwards along the coastline to form beaches, culminating in a long recurved spit at Tangadiou. Although there has been mineral prospecting within this catchment, it has not been affected by opencast mining, and the presence of gravel in the river channel and along the coastline north of the delta cannot be attributed to mining impact. It is thus evident that if a source of coarse-grained sediment (in this case Pleistocene terrace and fan gravels) is naturally available within such a river catchment, such material can be carried down to the coast, notably during episodes of floodwater discharge that occur during tropical cyclones. Delivery of coarse sediment loads to river mouths is thus not in itself a reliable indication of the impact of opencast mining in New Caledonia.

Nevertheless, it appears that the addition of gravelly beaches to the coastline at and north of the Koumac delta is a very recent phenomenon, for the older parts of the delta are dominated by sediments no coarser than sand. A probable explanation is that slope wastage, and especially the erosion of Pleistocene river terraces and piedmont fans, results from increased and accelerated runoff due to the reduction and impoverishment of the vegetation cover, mainly forests, within this catchment by bushfires. The Melanesian people used fire extensively in this region, and bushfires have occurred frequently in the era of European occupation. If this is the case, the delivery of a gravelly load to the coast by the Koumac during floods is indeed an anthropogenic impact, even though it is not due to opencast mining.

Oué Bouameu

South of Koumac the ultrabasic Kaala massif is fronted by a broad piedmont fan composed of a variety of coarse to fine sediments washed down from the steep slopes during Pleistocene times. In the Holocene this has become a relatively stable landform, crossed by a series of parallel small watercourses, but one of these, the Oué Bouameu (catchment: 13 sq km), has become larger and deeper than the others, and is carrying a load ranging up to cobbles and small boulders, much of which has been derived from spilling and slumping waste fans around the opencast nickel mines on Mount Kaala. The Oué Bouameu has taken a variety of courses across a lobate fan at Karembé (fig. 13), where recurrent flooding of a

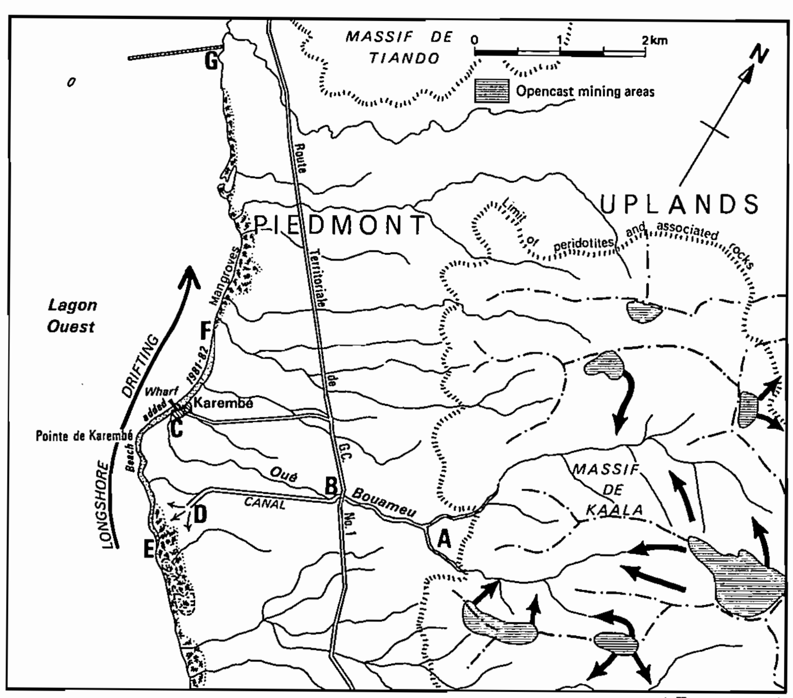

FIG. 13. The Delta of the Oué Bouameu River at Karembé. The river carries a large gravelly load downstream from A to B and formerly delivered it to the coast at C, but recently a diversion canal has been constructed to D and now the discharged sediment reaches the coast near E, from where it has drifted northward as far as F. Eventually it will accumulate alongside the breakwater at G, to the north.

farmstead has prompted the cutting of an artificial channel to deflect the river southwards. During Cyclone Gyan, when over 430 mm of rain fell within a period of 24 hours at Koumac, the Oué Bouameu flowed torrentially and carried large quantities of sediment ranging from fine red clay up to cobbles 12 cm in diameter downstream to the coast (plate 6), where the coarser sand and gravel have accumulated as a beach in front of a shoreline that was previously mangrove-fringed and fronted by tidal mudflats (plate 7).

This beach has grown northwards (plate 8), past the Karembé wharf, where a rock breakwater is under construction to the north to intercept the drifting beach material and prevent it spreading to the Koumac shore. Wave action is thus redistributing material that was brought down to the coast in the last flood. Near the southern end of the deposited sand and gravel, southerly waves have built a cuspate spit, which is being driven back into mangrove-covered clay flats in the form of a chenier.

Red clay washed down from the hilltop mine has been deposited in the nearshore zone, and the sea is stained red-brown by this sediment in suspension. Local people believe that this pollution has impeded coral growth in nearshore waters, and that the inshore fishery has also been impoverished, both in terms of quality and quantity of fish available. But apart from structural damage during the flood (plate 9), the mangrove areas have been little affected and mangrove growth is continuing on red mud accretion. Construction of barrages and sediment traps around the opencast mine is now reducing the sediment yield, but substantial masses of waste material have already spilled and slumped down slopes in the headwaters of the Oué Bouameu, and much of this will be carried down to the coast during future episodes of flooding.

Iouanga

Like the Koumac, the Iouanga (catchment: 522 sq km) drains an area of varied geology, mainly schists, sandstones, and phthanite cherts. It has so far been little affected by the opencast nickel mining on Mount Kaala and on the Massif d'Ouazangou-Taom; its channel load at Kaala-Gomen is a mixture of sand and gravel, the latter mainly of chert. Some of this material reaches the

PLATE 6. The Oué Bouameu River Looking Downstream from the Highway Bridge. The channel was greatly widened and shallowed by accretion when floodwaters brought down large quantities of mining waste from the Kaala massif, drained by its headwaters. During Cyclone Gyan, in December 1981, large amounts of sand and gravel were swept down to the mouth of this river and deposited along the coastline at Karembé.

PLATE 7. Accretion of Sand and Gravel on the Shore at Karembé, South of the Ruined Wharf. This material consists largely of mining waste brought down by the Oué Bouameu River.

PLATE 8. Shore Accretion North of Karembé. The formerly muddy, mangrove-fringed coast has been replaced by a beach of sand and gravel brought down by the Oué Bouameu, mainly during the floods that accompanied Cyclone Gyan.

PLATE 9. Mangroves on the Deltaic Plain of the Oué Bouameu at Karembé, Killed by the Deposition of Red Clay during the Floods That Accompanied Cyclone Gyan

delta region, where ridges of fluvial sand and gravel, with some shelly and coralline material, have been built up as fringing beaches or cheniers emplaced on clay plains. However, the seaward fringes of this delta are mainly mangrove swamp, and gravel beaches and spits of the kind seen north of the Koumac delta have not yet developed. In the past few years there have been changes in the meandering channel downstream from the highway, associated with aggradation and bank erosion, but this does not seem to be a direct consequence of anthropic factors.

Tinip

The Tinip stream (fig. 14) drains a small catchment (area: 12 sq km) on the western slopes of Mount Ouazangou. Like the Oué Bouameu, it has been strongly affected by opencast nickel mining in its headwaters, the stream channel having been widened to accommodate an increased and coarsened sediment yield derived from the waste products of mining. An air photograph taken in September 1976 shows a large mass of mining waste in the valley on the western slopes of Mount Ouazango (see fig. 14), and this has subsequently moved down the river. In October 1980 the Tinip had an aggraded channel at the highway crossing (plate 10), mining waste having reached this sector, but by October 1982 much of this material had been sluiced downstream, re-exposing the trunks of trees that had been killed and buried by the earlier aggradation (plate 11). This change implies some success in attempts to control the flow of overburden discharged from the hilltop mine, the last major floods (Cyclone Freda in March 1981, then Cyclone Gyan in December) having driven channel fill down the river where the channel has widened and aggraded (plate 12). In the Baie de Gomen a delta of red mud, sand, and fine gravel is developing. The inshore waters of the Baie de Gomen are stained red with suspended clay, and the prop-roots of Rhizophora are also coated with red clay, although this has not prevented their continued growth. A cloud of suspended clay extending south from the river mouth is visible on an air photograph taken in 1976, but is absent from a 1954 air photograph of the same area, taken before the periods (1955–1964 and 1967–1977) of intensive mining on Mount Ouazangou.

The Tinip is thus an example of a stream that has been modified along the whole of its length by the inflow of mining waste materials from its headwater regions. The coastline at its mouth has been modified by the formation of an "anthropic delta," and the nearshore waters show the effects of red clay pollution, which has not proved adverse to mangrove growth but may well have depleted local fish populations.

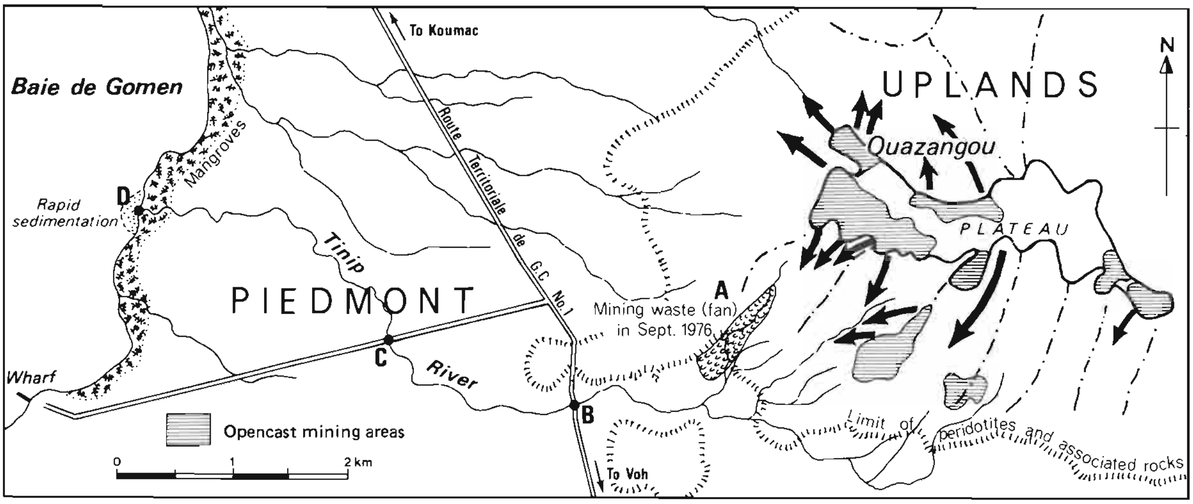

FIG. 14. Impact of Mining Waste on the Tinip River. In September 1976 the waste fan was at A, in October 1980 it had aggraded the channel near the highway at B (plate 10), and by October 1982 it had moved down to the sector near C (plate 12), while fine sediment (red clay) was being deposited at the river mouth, D.

PLATE 10. The Aggraded Channel of the Tinip River, as Seen from the Highway Bridge Looking Upstream to the Mine-scarred Massif d'Ouazangou-Taom. The photograph was taken on 19 October 1980 (cf. plate 11).

PLATE 11. The Channel of the Tinip River (same view as plate 10), as Seen on 28 October 1982. Discharge of flood waters during Cyclone Gyan excavated this section of previously aggraded channel to reveal the stumps of trees that lined the narrow, incised watercourse prior to the aggradation of mining waste. The material excavated has been carried further downstream (plate 12).

PLATE 12. Some of the Material Excavated from the Channel of the Tinip River between 1980 and 1982 (plates 10 and 11) Has Been Deposited to Aggrade the Channel Further Downstream (cf. fig. 14)

Ouaco

Like the Tinip, the Ouaco (catchment area: 35 sq km) has been much modified by the effects of opencast mining on Mount Ouazangou. Its sediment yield has been increased and its deltaic shoreline is prograding as the result of the additional sediment supplied to the river mouth. The nearshore sea water here is generally discoloured by red clay washed down the river and retained in suspension.

Poué Koué

Draining the southern slopes of Mount Ouazangou, the Poué Koué (basin area: 32 sq km) has also been greatly affected by the opencast hilltop mining. In fact, the mining waste is received from three small peridotite massifs in the headwaters (Ouala, Tsiba, and Oualéat), which have been intensively mined. Being only four to six km inland, their wastes have quickly reached the river mouth. The river channel is overloaded with a mixture of sediment ranging from red clay to small boulders, and the lobate piedmont fan that formed this part of the coastline is being prograded by the addition of this material to form a delta around the river mouth. Extensive red staining has polluted the coastal waters off the Poué Koué.

Taom

Draining the southern slopes of the Massif d'Ouazangou-Taom, this river (basin area: 105 sq km) has been less affected by the inflow of mining waste, which has not spread as far downstream as in the Poué Koué. Mining has occurred at only three sites 15 to 20 km upstream, so that the effects have been less dramatic than in the smaller Tinip and Poué Koué basins. At the highway bridge the watercourse is slightly incised and gravelly, but the sediment yield to the mouth of the river has been small and the effects of mining activities on coastal and nearshore environments have so far been only slight.

Oué Pouanlotch

This river drains a deep gorge between Mount Taom and Mount Témala. The upper part of its catchment (area: 92 sq km) has not been affected by hilltop nickel mining, but the summit area and the eastern slopes of Mount Taom have been intensively prospected, leaving a dense network of trackways (visible on 1976 air photographs). Below Boyen the river flows across a Pleistocene alluvial plain, and although its channel load at the highway crossing contains peridotite boulders from the massif, the augmentation of sediment yield to the coast has so far been meagre and the effects of mining activities remain very slight.

Témala

Although nickel mining has taken place in the coastal Mount Katépahié and Massif de Voh regions, the sediment yield from the Témala catchment (352 sq km), like that from the adjacent Oué Pouanlotch, has been more affected by the soil erosion that has resulted from the grazing of pastures on basaltic hill country in the relatively dry environment around Témala (Iltis 1979). Occasional heavy rains have washed substantial quantities of grey clay and silt from these eroding hillsides into the Témala River, and downstream to the extensive marshes and mangrove swamps on its delta plains west of Voh. At the highway bridge the river is clear, with shoals of grey sand and gravel, and the impact of the opencast mining activities here and at the river mouth has also been slight.

Voh

The Voh River (catchment area: 227 sq km) drains an extensive upland region dominated by the large ultrabasic Massif de Koniambo, the north-western part of which is called the Massif de Voh. Hilltop mining was intensive here from 1900 to 1940, when the region was the leading producer of nickel in New Caledonia, exceeding even the Thio area. Hillsides remain scarred by this mining activity and there is no doubt that the Voh and its tributaries had augmented sediment loads during the mining phase, but the inflow of mining waste has diminished, and the river channel, which was probably widened as the augmented sediment yield passed through, now appears relatively stable. It is likely that the delta at the mouth of the Voh has been prograded as the result of augmented sediment discharge, but these effects have diminished and the present mangrove-fringed coastline is no longer strongly affected by these historical mining activities in the hinterland.

Massif de Koniambo

This ultrabasic massif, between Voh and Koné, is one of the larger areas that has so far not been mined extensively for nickel; it is regarded as a reserve for future nickel production and will be exploited in due course. Meanwhile the summits and slopes are almost intact, their weathered lateritic mantle held in place beneath maquis scrub, and the piedmont apron on their seaward flank shows a number of narrow, gravelly watercourses (e.g., Le Pandanus, La Confiance) that have not been modified by mining activities. Their present dimensions and sediment loads are thus contrasted with those of the Oué Bouameu and Tinip streams, which were once like this.

Koné and Pouembout

Ultrabasic terrains at the eastern end of the Massif de Koniambo form only a small proportion of the catchment (area: 272 sq km) of the Koné and its tributaries, and at the highway bridge the river carries a mainly sandy load downstream to a mangrove-fringed delta that is not prograding as rapidly as the deltas of rivers strongly affected by mining activities. The same applies to the adjacent Pouembout river system (catchment basin: 339 sq km). However, the left bank tributaries of the Pouembout are influenced by inflow of gravelly peridotite from former mines on the crest of the Massif de Kopéto, notably during floods that accompany cyclones. This coarse material extends down to the confluences with the Pouembout, finer sediment having been washed further downstream.

Tiaoué

The Tiaoué has a relatively small catchment (66 sq km) on the western side of the Massif de Kopéto-Boulinda. Although there has been some prospecting and hilltop mining on the upper fringe of this catchment, the river system has been little affected. It carries a sparse load of grey gravel, sand, and silt, largely derived from the erosion of basaltic hill country, and has not yet built a delta.

Népoui

The Népoui, and its tributary, the Rivière Salée (combined catchment area: 177 sq km), drain deeply dissected ultrabasic massifs where opencast nickel mining has been extensive (fig. 15). In the 1970s "boom" period this was the most productive mining region in New Caledonia, but it has been overtaken by Kouaoua, and in fact production ceased from the Massif de Kopéto on 1 January 1983. As a result of mining, vast masses of overburden have flowed and slumped down the slopes bordering hilltop mines in the Massif de Kopéto-Boulinda (and especially in the Massif de Graunda-Boulinda), and the river channels of the Népoui (as of the neighbouring

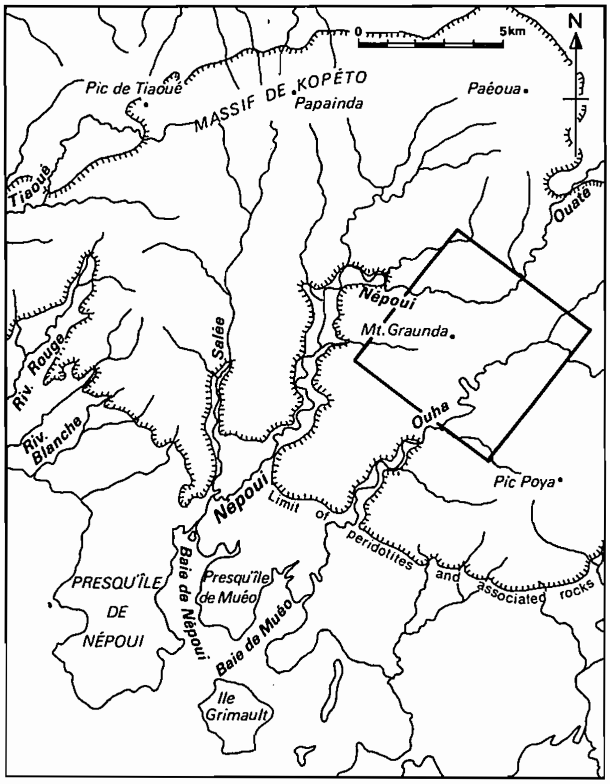

FIG. 15. The Népoui River Catchment. The square indicates the area covered in figure 16.

Ouha to the south-east) have been greatly modified, widening to accommodate large quantities of sediment ranging from red clay through sand and gravel to cobbles and boulders. Figure 16 shows details of the impact of this opencast mining on the geomorphology of Mount Graunda, between the Népoui and Ouha valleys. Mining has here removed much of the summit plateau, and hillside waste fans form depositional cones, one of which has partly blocked the Ouha valley, forming a ponded river. The channels of the Népoui and Ouha have become wide and gravelly, the streams flowing through braided channels. Plates 2, 3, and 13 show the features produced by the inflow of mining waste to the Népoui, in contrast with the unmodified river channel upstream (plate 14).

The Népoui River flows into an elongated embayment (fig. 17) alongside the limestone Presqu'île de Népoui, and at its mouth mangroves are extending rapidly on to broad red mudflats (plate 15) produced by the deposition of iron-stained clay washed down from the disturbed lateritic overburden in the hilltop mines. Comparison of air photographs taken in 1954 and 1976 show that the mangrove fringe advanced seaward by up to 400 metres on the shores of the Népoui delta in this period, and this advance is continuing. The waters of the Baie de Népoui have been shallowed by this sedimentation and red clay staining is extensive. Successive floods are washing coarser sediment down the Népoui. In addition to red clay, some sandy material has arrived at the river mouth, pebble gravels have extended to the lower reaches, and eventually coarser gravel will arrive at the coast. Already severely affected by mining activities, the Népoui delta region is destined to receive much more sediment of gradually increasing calibre. Mangrove growth has not been impeded, and has probably been stimulated by the accretion of red mud, but as coarser sediment reaches the delta area, it is likely that the mangrove cover will be disrupted.

As mentioned already, the Ouha (catchment: 84 sq km) has also been affected by opencast mining on the crests of the Massif de Graunda-Boulinda. At the highway crossing it carries a sandy load stained by red clay, which is being delivered to its mouth. The sea is stained red in the Baie de Muéo off the growing delta of the Ouha. However, the advance of this delta is clearly less rapid than that of the Népoui. Instead of a general spreading of mangroves on to accreting mudflats, the advance is here by way of scattered mangrove establishment.

Baie de la Poya

The Poya and its tributaries (catchment: 418 sq km) drain a broad lowland flanked by the Massif du Boulinda to the north and the Massif du Mé Maoya to the east. Both areas have undergone extensive hilltop nickel mining, and the upper tributaries have received sediment yields augmented by mining waste; but the Poya is so far little affected. By contrast, the Muonio to the north-west flows directly from the southern slopes of the Massif du Boulinda into the broad, shallow Baie de la Poya, and has an aggraded channel of coarse material stained by red clay. The Moindah River (catchment: 165 sq km), draining directly from the mined Mé Maoya massif to the west, is also delivering red-stained silt and clay derived from mining waste into the Baie de la Poya. Coarser material (pebbles and boulders of peridotite) has been transported five to

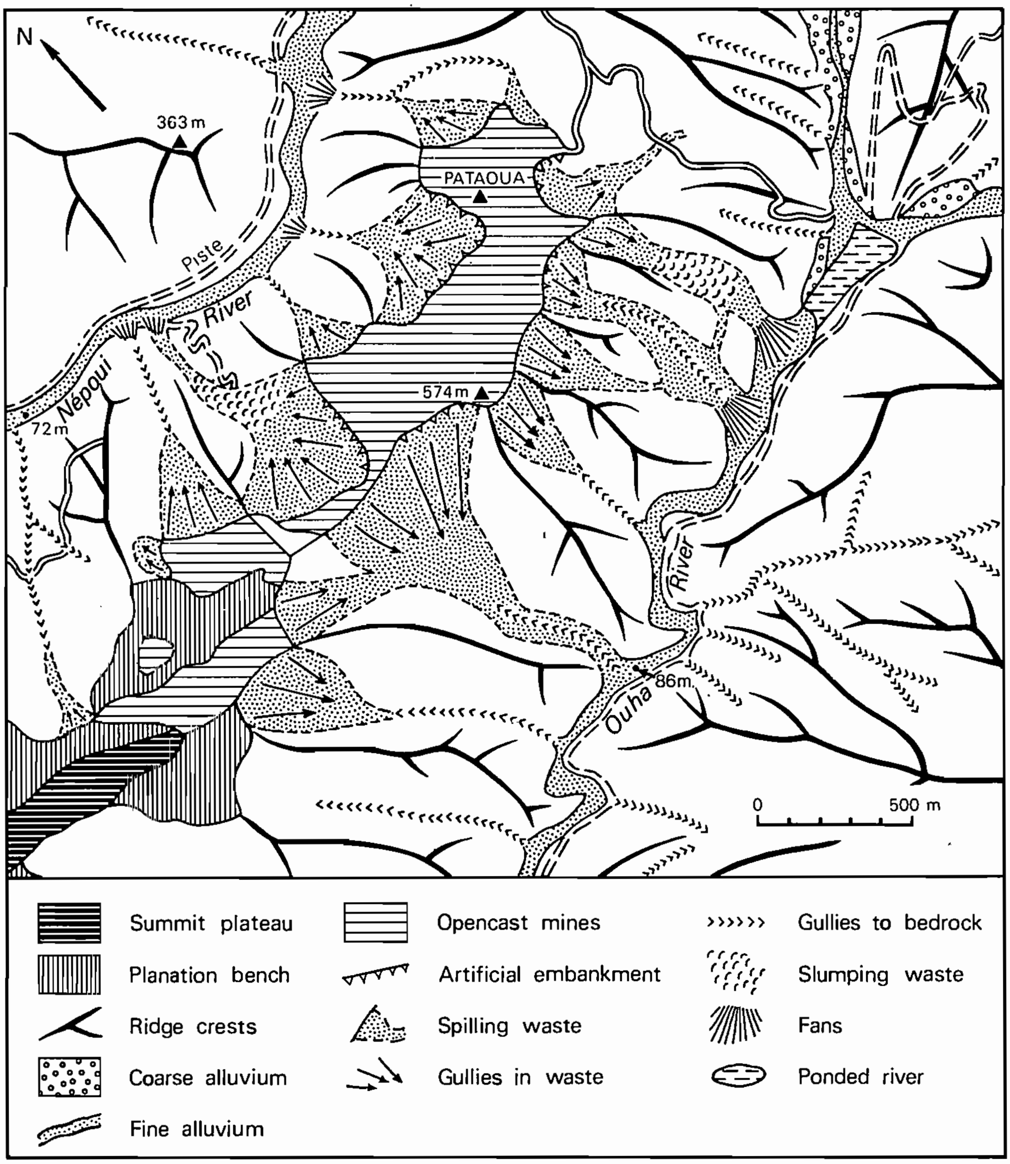

FIG. 16. The Effects of Opencast Mining on Mount Graunda (Massif de Kopéto-Boulinda), between the Népoui and Ouha Valleys. The sketch-map is based on an air photograph (scale 1:20,000) taken by the Institut Géographique National on 24 September 1976.

six km down from the massif along a deep gorge, but is deposited well upstream from the river mouth.

Rivière du Cap

Backed by the Mé Maoya massif, the catchment of the Rivière du Cap (area: 174 sq km) is the largest of several river systems draining to the coast between Poya and Bourail. Its right bank tributaries have built broad piedmont fans and terraces, while the main course flows alongside the siliceous sandstones and cherts of the Montagnes Blanches to enter the sea by way of a small delta built into an embayment. Downstream the channel load includes peridotitic gravel and cobbles supplied by the right bank tributaries. The lower watercourse and the delta receive red lateritic clay derived from former opencast nickel mining on the southern slopes of Mount Djiaouma. The river has thus been moderately affected by mining activities.

Néra

The Néra and its tributaries form one of the larger river systems on the west coast (catchment: 546 sq km), uniting near Bourail to enter the Baie de

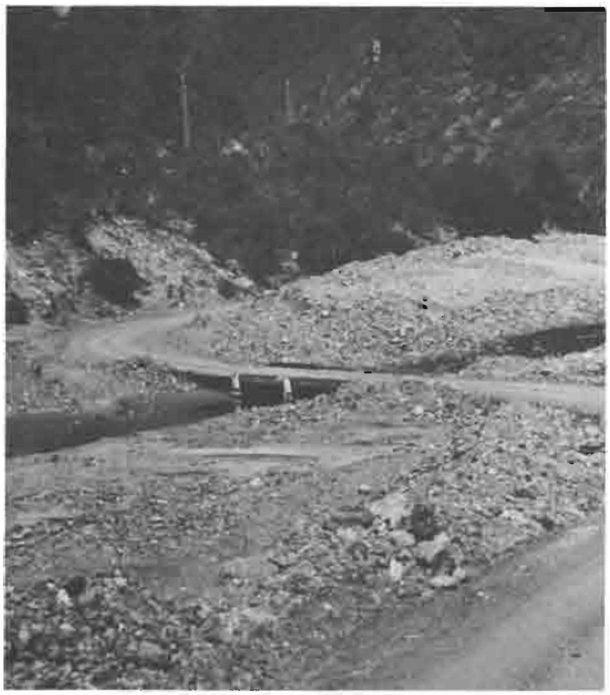

PLATE 13. Aggraded Channel of the Népoui River Downstream from the Nickel Mining Region. The watercourse here was previously similar to that persisting upstream from the mined area (plate 14).

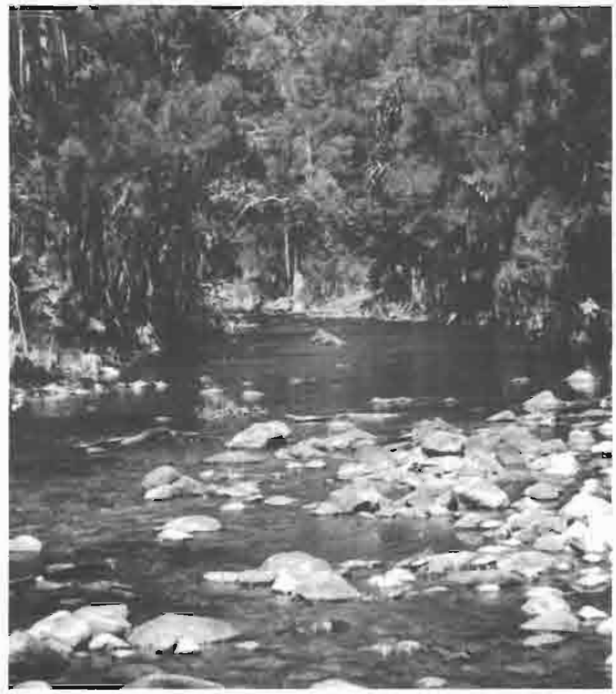

PLATE 14. The Channel of the Népoui River Upstream from the Sector Affected by Inflow of Mining Waste. Many of the rivers of New Caledonia were like this before deposition of mining waste widened and aggraded their channels.

PLATE 15. The Mangrove-fringed Delta of the Népoui River. The deposition of red clay derived from mining activities upstream has here shallowed the Baie de Népoui and widened the intertidal zone, thus promoting rapid seaward spread of pioneer mangroves onto red mudflats. Contrast the effect of blanketing of mangroves at a higher level on the Karembé delta (plate 9).

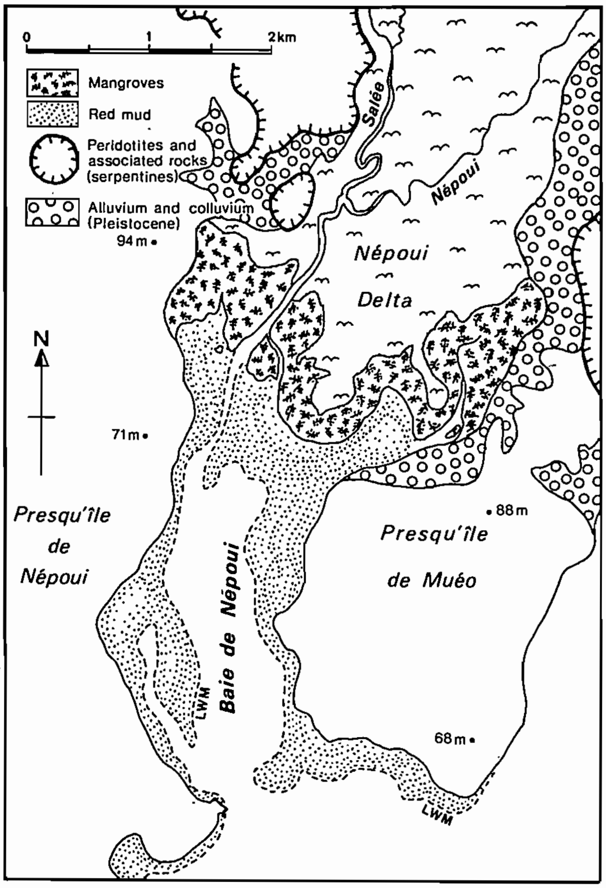

FIG. 17. The Népoui River Delta

Gouaro by way of a deltaic plain fringed by sandy beach ridges. Much of the catchment consists of hilly terrain on basalts and sedimentary rocks, but ultrabasic massifs occur on the higher inner margins, which form the eastern edge of the Massif du Mé Maoya thrust outliers.

Abandoned cultivation terraces (*tarodières*) are extensive in this and other catchments on the central west coast (plate 16), indicating a pre-colonial phase of land management by indigenous people, who may have perceived that their utilization of steep slopes was resulting in soil erosion; they imply a response to an earlier phase of anthropogenic erosion on slopes that had been cleared and cultivated, but the details of this have not been researched.

Of the various Néra tributaries, the most affected by mining is the Téné, a tributary of the Boguen, which has its headwaters in the Massif de Téné, but the effects of this do not yet extend far downstream and the Néra estuary is a clear river with shoals of grey silty sand and some gravel. Sandy material washed into the Baie de Gouaro has been built into beaches and beach ridges by ocean swell that enters by way of a gap in the outlying coral reefs.

Nessadiou

The Nessadiou (catchment: 87 sq km) follows a meandering course westward from the hill country north of Moindou to reach the sea by way of a small bay-head delta south of Bourail. Its catchment consists mainly of Mesozoic and Eocene volcanic and sedimentary formations, and its yield is a mixture of silt, sand, and fine gravel. It is an example of a river system unaffected by mining activities, but with a sediment yield probably somewhat augmented by the clearing and burning of vegetation on hilly country in its upper catchment. Here, as elsewhere on the west coast, recurrent burning to maintain pastures has converted extensive areas of sclerophyllous forest into grassy savannas with areas of niaouli scrub, formerly confined to low-lying areas. This weakened vegetation cover results in accelerated runoff and soil erosion.

Moindou

The Moindou (catchment: 125 sq km) is another basin without ultrabasic formations and opencast mining. There has been underground mining of coal in the Moindou region, but this has had a negligible impact on river sediments. The Moindou carries mainly clay, silt, and sand down to its marshy mangrove-fringed bay-head delta.

La Foa

This extensive river system (catchment: 438 sq km) has headwaters in Palaeozoic and Mesozoic volcanic and sedimentary formations. Some serpentinite outcrops also occur, but have not yielded exploitable minerals. La Foa has not been affected by mining activities. In its lower reaches it carries mainly clay, silt, and sand into a winding estuary opening into the Baie de Téremba.

Ouaméni

This river system drains hilly and mountainous country (catchment: 175 sq km) north-west of Bouloupari, including the western slope of an ultrabasic massif, Mont Do, where hilltop mining has not taken place. The Ouaméni delivers a load of fine-grained sediment, no coarser than sand,

PLATE 16. Abandoned Hillside Terraces near Col des Roussettes, North of Bourail, Date from a Pre-colonial Phase

to its delta in the northern part of the Baie de St. Vincent.

Ouenghi

Opencast hilltop nickel mining has been carried out on the western end of the peridotitic Grand Massif du Sud on the margins of the Ouenghi catchment (area: 270 sq km), and the sediment load of this river has been augmented by red clay and by gravelly material derived from mining waste. These effects have been reduced, however, by systematic mechanical settling of colloidal iron hydroxides and by the building of large sediment-trapping boulder dams around the opencast mines of the Massif de Kongouhaou, and the impact of mining activities in the lower reaches of the river, on the Ouenghi delta, and in the adjacent Baie de St. Vincent have been slight. Nevertheless, recent attempts to introduce oyster farming in the eastern part of this bay and the building of shrimp ponds in the Baie de Kuara, adjacent to the Ouenghi delta (fig. 18), are activities that are periodically impeded by red-clay pollution from recurrent river flooding.

Tontouta

Like the Ouenghi, the Tontouta and its tributaries (catchment: 476 sq km) drain a peridotite hinterland where opencast mining has been extensive on mountain crests, and on hillslopes, some only a few kilometres from the coast. The river carries extensive gravelly shoals as well as sand and finer material, and has shallowed nearshore areas around its mouth in the southern part of the Baie de St. Vincent. The impact of mining activities has been stronger than in the Ouenghi catchment because of the lack of conservation works and because of the intensity of mining and waste generation in the Tontouta catchment in the last 20 years. The sediment yield has increased at the river mouth, where mangroves have become more extensive, spreading back on to the delta below Mont N'dui, as seen when 1954 and 1976 air photographs are compared.

Dumbéa

Some small-scale localized nickel mining has occurred in the headwater regions of the Dumbéa River (catchment: 233 sq km), but the effects on river loads have been slight; as in other drainage basins near Nouméa, mineral prospecting has been forbidden in order to maintain water quality. The sediment yield at the river mouth, where a mangrove and marsh-covered delta (fig. 19) is growing, consists mainly of clay, silt, and sand, and the effects of mining activities have been only slight. Some mangroves alongside the new

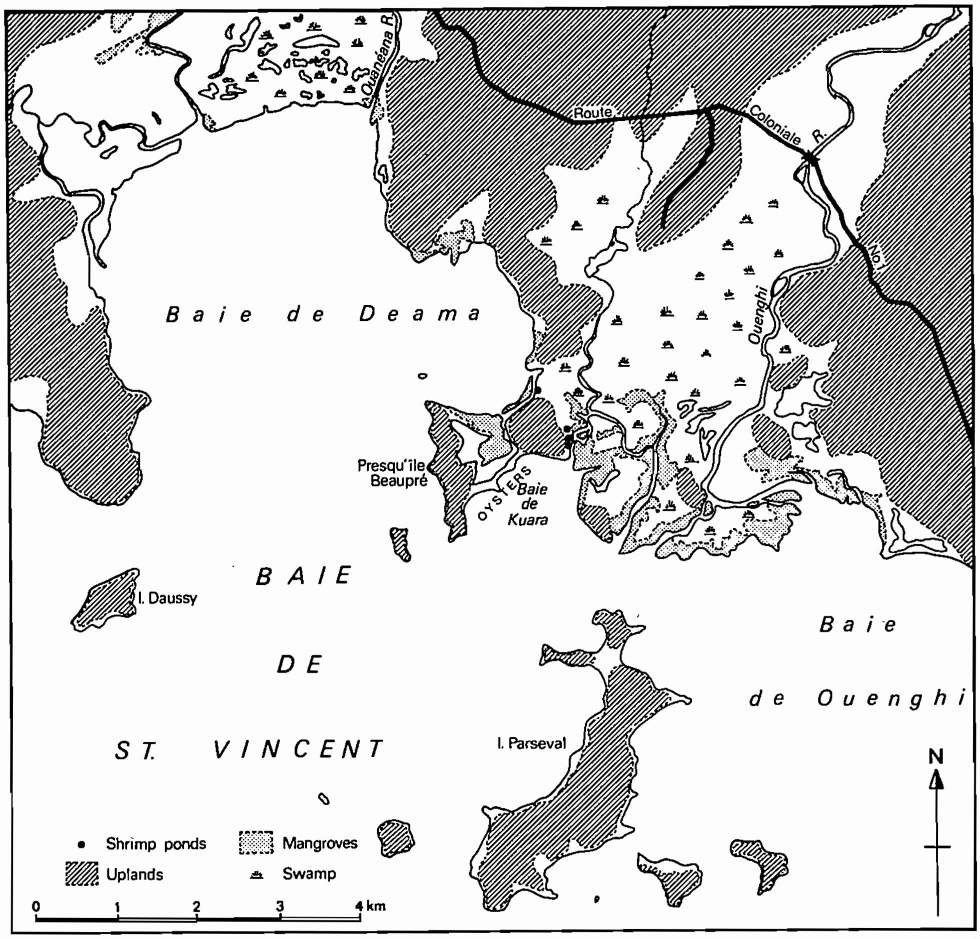

FIG. 18. The Ouenghi River Delta. The introduction of oyster farming near the western shores of the delta and the construction of shrimp ponds are recent activities that will require freedom from red clay pollution of the kind that has affected other west coast deltas.

highway have been killed by waterlogging due to road construction, rather than by changes resulting from hinterland mining.

La Coulée

With a catchment (area: 92 sq km) almost entirely in the ultrabasic Grand Massif du Sud, La Coulée carries sands and gravels stained by red clay, a sediment yield augmented by hilltop mining activities which continued into the 1970s. The river is extending its delta into the southern part of the Baie de Boulari, where tidal mudflats are being deposited in a red-stained sea. Similar features are seen on a smaller scale along the Plum stream to the east of Mont Dore, where the hillsides are scarred by gullies and landslides in the weathered red lateritic mantle.

Rivière des Pirogues

This river (catchment: 152 sq km) has its headstreams adjacent to the Upper Yaté basin, a sparsely vegetated region of peridotitic karst, in the vicinity of Ouénarou, where river piracy is in progress. The headwater region shows features formed by differential erosion of gabbros and granodiorites associated with the peridotite Massif du Sud, and has not been mined. The lower part of the catchment has been much affected by opencast mining, and by gullying and slumping of red ferruginous lateritic mantles on valley-side slopes. More than 60 years ago there were reports of rapid erosion as a sequel to mining in this area (Compton 1917). The Rivière des Pirogues has a load of sand, gravel, and cobbles stained by red clay, which is rapidly filling its es-

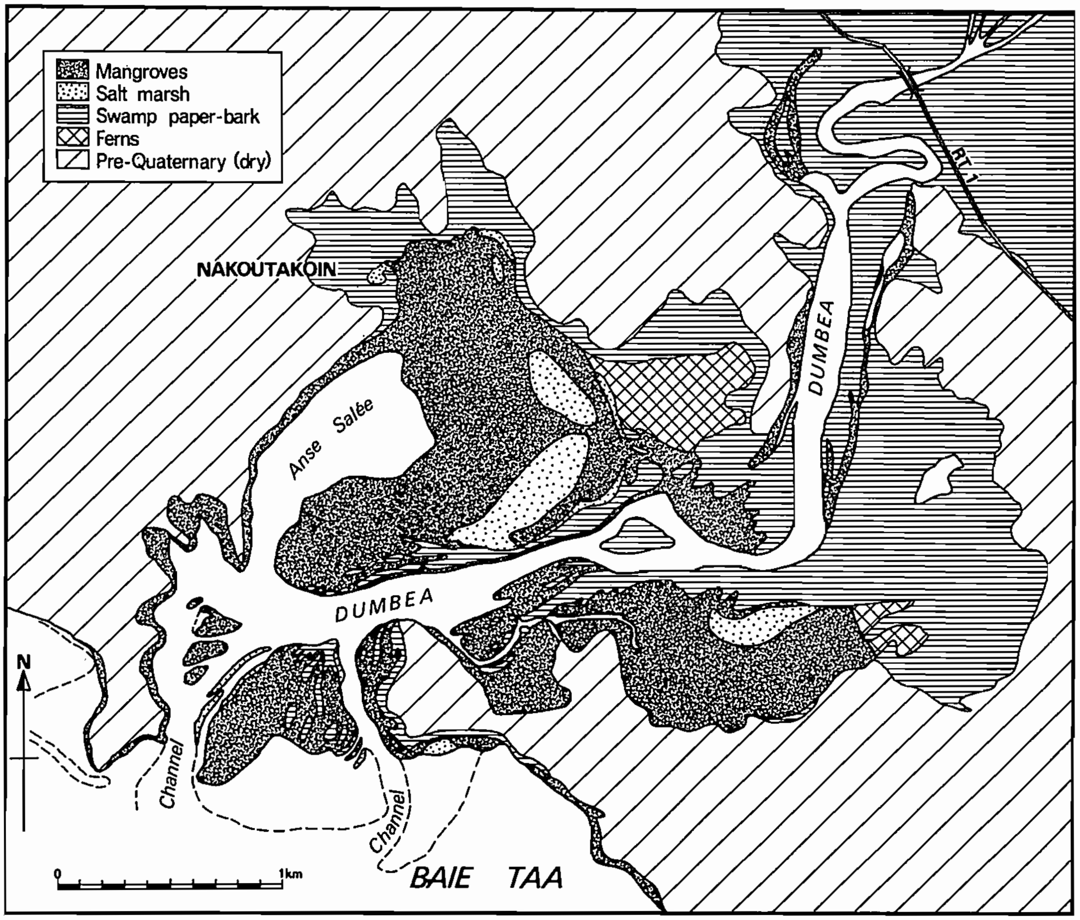

FIG. 19. Vegetation Communities on the Dumbéa Delta (after Baltzer 1969). Extensive mangroves are spreading forward onto accreting intertidal mudflats.

tuary in the lee of a sand spit built at the river mouth. The adjacent sea, shoaly with down-washed sediment, is red-stained. Similar features occur in the small Rivière Ngo catchment to the south, opening into Baie Ngo (plate 17).

Baie de Prony

The branching ria of the Baie de Prony receives a number of small streams, including the Rivière Bleue and the Ruisseau de la Bergerie, which carry increased loads of red clay as a sequel to opencast mining between 1955 and 1968 of the ferruginous crust of the laterite mantle as an iron ore. Extensive areas north-west of the Baie de Prony have been denuded of vegetation and soil by this extraction, and persist as a red clay desert, within which gully erosion is developing. The streams are washing red clay down to stain beaches and nearshore waters in the small embayments (e.g., Baie de la Somme) which branch from the Baie de Prony. Divers have reported unusually large madrepore species growing in turbid waters here, indicating that some corals may be able to adapt to the changed environment. The deeper waters appear to have been little affected, and coral growth remains vigorous offshore.

Koué

Draining southward from the escarpment bordering the Plaine des Lacs, this river (catchment: 150 sq km) has some headstreams in the area affected by opencast iron ore mining, but does not yet show significant modification of its channel, which opens into a winding ria.

Kuébéni

Typical of streams descending from headwaters in the peridotitic karst region of the Plaine des

Lacs, the Kuébéni (catchment: 38 sq km) carries a load of red clay and pisolitic ironstone sand, much of which is being deposited in the small inlet at its mouth, in the lee of the emerged reef islands of Nou and Néaé. Opencast iron mining in the Goro region between 1937 and 1941 and the subsequent bulldozing of superficial deposits have increased this sediment load and accelerated deposition at the river mouth. Systematic prospecting in the 1970s in this southern part of New Caledonia revealed extensive reserves of low-grade nickel ore in the superficial formations, and it is possible that large-scale mining will proceed here in the future.

Yaté

The original Yaté dam was completed in 1927 and has been replaced by the modern barrage, built between 1955 and 1958. As a result, the Yaté (catchment: 450 sq km) has delivered little sediment to the coast. The extensive, branching reservoir acts as a sediment trap, receiving red clay and pisolitic sands from the bordering slopes, a supply that has been augmented by nickel and some chromium mining, road-making, prospecting, and the depletion of vegetation by recurrent bushfires.

Pourina

This basin (catchment area: 98 sq km) occupies the southern part of the eastern slopes of the Grand Massif du Sud; the watershed rises about 1,000 metres above sea level and slopes are steep. Erosion is a dominant process, especially in the middle and lower catchments, where the forest cover thins out. Mining activity has been limited to nickel prospecting and local exploitation of chromium. At the river mouth a small sandy barrier nestles at the head of an embayment and has been slightly enlarged by the accumulation of ferruginous and chromitic sands during the past 20 years, without much effect on the outlines of the embayment.

Ouinné

This catchment (146 sq km) is even more mountainous than that of the Pourina. The river mouth consists of a small delta built into a lagoon behind a large sand barrier on which the mining settlement of Ouinné stands. The configuration of the delta has been modified by the cutting of channels to allow barges to load mineral ore close to the mines. Nickel-bearing formations occur between 200 and 300 metres above sea level on hillsides overlooking the delta and were mined in the late 1960s. Air photographs taken in 1976 show that the mouth of the Ouinné had not yet been affected by augmented sediment supply, but the small Ué River to the south, draining coastal hills where mining occurred, had been almost blocked by the deposition of waste material. It is feared that the effects of nickel mining will increase here during the

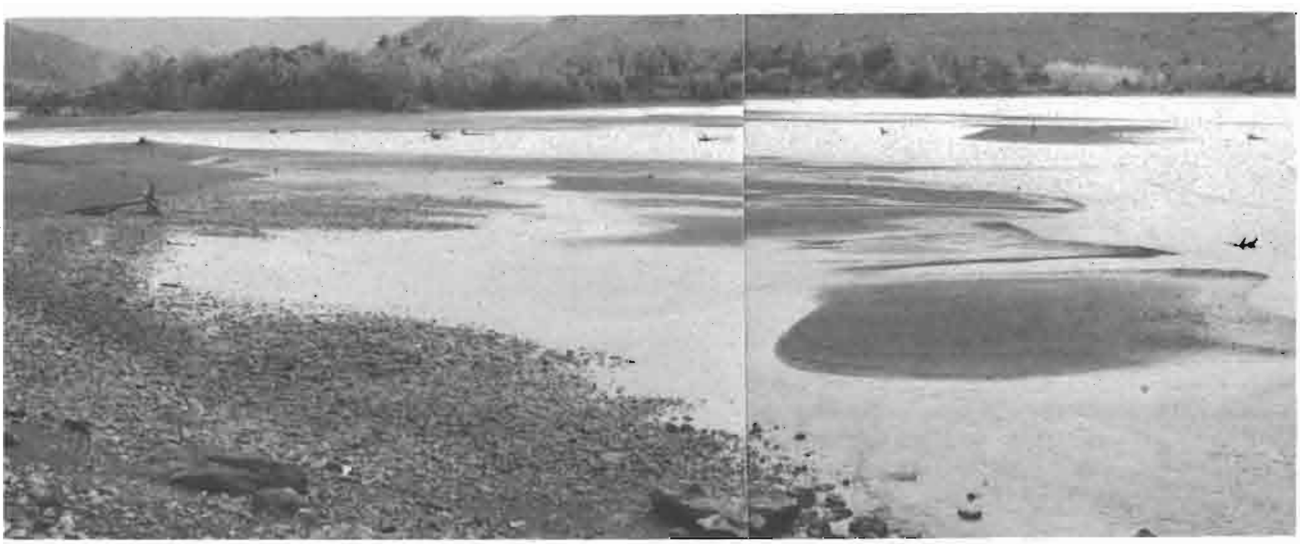

PLATE 17. Mining-waste Shoals. Nearshore shoals of sand and gravel produced by floodwater deposition from streams with loads augmented by mining waste are reworked by waves and moved shoreward at the head of Baie Ngo, south of Nouméa.

next few years in spite of the reduction in mining activity and the building of dykes to partly enclose the river mouth.

Kouakoué

This very mountainous small basin (catchment: 77 sq km) is dominated by the ridge of the Massif de Kouakoué, which rises to 1,501 metres above sea level. It has been subject to exploration but not to mineral exploitation. The lower part of the valley widens into a delta. Although the basin has not been mined, sedimentation appears to have increased at the river mouth, where a sand spit built of fluvial sediment reworked by wave action grew substantially between 1954 and 1976.

Ni

Mineral prospecting has occurred within the basin of the Ni (catchment: 173 sq km), and construction of exploration roads has strongly increased sediment yield. Comparison of air photographs taken in 1954 and 1976 shows sand accretion in the delta, where the river splits into three distributaries. Two of the three outlets are now partially obstructed by a large fluvial sand and gravel barrier beach built during this period.

Ngoye

Nickel mining has occurred at several places within this 93-square-kilometre catchment, but the effects on the river and its delta have so far been slight. The delta, which (like the Kouaoua delta) includes successively formed beach ridges, is bordered by a littoral spit, which grew between 1954 and 1976 to reduce the outflow channel to the sea to a narrow pass.

Comboui

Dominated by the high ranges of the Humboldt massif, this basin (catchment: 180 sq km) has also been subject to mineral prospecting, which has greatly increased fluvial sediment yields. Large quantities of fine-grained sediment have also been derived from serpentinite hills up to 300 metres high in the lower valley, where ravine dissection has been in progress since before the prospecting era, and perhaps from pre-colonial times. Nourished by these inputs, the Comboui has a widened channel leading to a substantial delta, with several distributaries, one of which has been sealed off and two others narrowed as a result of growth during the last 20 years of sand spits built of wave-worked fluvial sediment.

Nimbo (Mba)

In this small basin (85 sq km) there has been only local nickel mining and some prospecting. These activities do not appear to have greatly affected the form of the river channel or its mouth, where a small littoral spit built of wave-worked fluvial sand has been driven landwards in recent years.

To N'deu

In the northern part of this basin (catchment: 72 sq km) there were two nickel mines at a low level about 3 km inland, worked intensively at the beginning of the century. Later a chromium mine was established, and nickel prospecting extended southwards. Sand and gravel discharged from the mines and areas of disturbance by prospectors aggraded the river channel and led to accretion on the delta, but these effects have diminished during the last few decades. Between 1954 and 1976 there were only minor changes on the deltaic shoreline of the To N'deu.

Thio

The Thio and its tributaries drain a region of 404 sq km, dominated partly by the ultrabasic uplands of the Grand Massif du Sud and partly by the volcanic and sedimentary formations of the Central Chain. Opencast hilltop mining has been extensive, especially on the slopes of Mount Ningua, and at the Mines Bornet above the Nakalé and Nembrou tributaries, where the river loads have undoubtedly been increased and coarsened as the result of these activities (plate 18). The most extensive mines, however, are in the coastal region, notably on the Thio Plateau, immediately west of the Thio township, where large-scale opencast nickel mining has been in progress for 80 years (fig. 20). The Thio Plateau contains the largest nickel deposit in the world. It has been mined continuously since 1901, and in eight decades has yielded almost 20 million tonnes of ore, producing about 450,000 tonnes of nickel and cobalt. In 1981 the Thio region was the second most productive mining centre (the first being Kouaoua) in New Caledonia.

The outcome has been massive generation of mining waste. Substantial masses of sediment have slumped down the hillside and have been

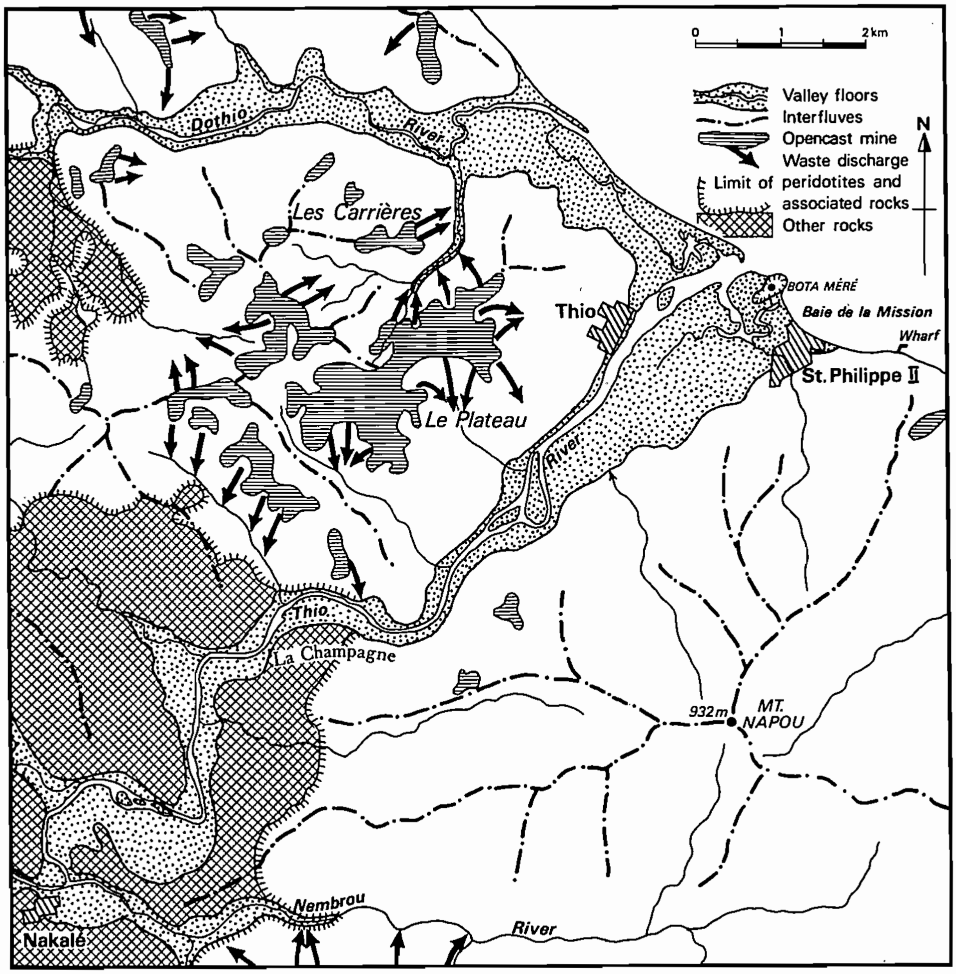

FIG. 20. Opencast Mining in the Thio Region Showing Patterns of Waste Discharge into Tributary Valleys of the Thio and Dothio Rivers

washed into the Thio River. It is believed that this river was formerly navigable by canoe upstream to Nakalé and by larger boats to a point near Les Pétroglyphes, about four km from the mouth, but infilling by sediment derived from mining waste has been rapid and such navigation is no longer possible. Below St. Pierre-Nakalé the impact of mining waste flowing into the Thio channel has been obvious, especially since the 1960s, although some changes had been observed twenty years previously, when mechanization of mining greatly increased the rate of waste production and downslope movement of discharged debris. Now the banks and bedload of the Lower Thio consist entirely of sand and gravel washed down from the Thio Plateau. An alluvial island 400 metres long has been completely blanketed by this debris, its scrubby vegetation cover destroyed.

The Thio delta, developed on either side of the rocky ridge of Bota Meré, has shown many changes in configuration on photographs taken in recent decades, and its present outlines differ substantially from those shown on the 1976 air photographs (plate 19). Each flood brings additional sediment, ranging up to sand and gravel, down to the river mouth, where it is sorted and built into spits and bars by wave action. Successive ground and air photographs indicate progradation relative to Bota Meré, with the formation, growth and widening of spits, the development of deltaic islets, the silting of distributary channels, and the infilling of small lagoons permitting mangrove establishment. Mining activities have thus accelerated delta development and augmented the sand supply to the beaches that extend northward from the mouth of the Thio. In recent years, rock dams and interception basins

PLATE 18. Hilltop Mining, Nembrou Valley. The association of hilltop nickel mining with discharge of mining waste down gullies and hillsides and broad gravelly and bouldery river channels has become a common feature in the region of ultrabasic massifs in New Caledonia.

PLATE 19. Thio River Delta, 2 November 1982. Changes in the configuration of the Thio delta have been recorded by numerous photographs taken from a viewpoint at the head of the old conveyor on the edge of the adjacent plateau.

have been built to reduce the amount of sediment yield from the mining areas.

Dothio

The Dothio (catchment: 77 sq km) drains a small basin north-west of the Thio that has a headwater region of volcanic and sedimentary rocks and several ultrabasic massifs near the coast where hilltop mining is active or has been carried out in recent decades. The slopes of the Thio Plateau have several areas where mining waste has spilled down and some large landslides. An attempt has been made to control the discharge of coarse waste material down the valley of the Wellington, tributary to the Dothio, by bulldozing boulder levees and a diversion dam (plates 20, 21, 22), but floodwaters will continue to deliver some of the finer material to the Dothio. The mouth of the river threads through a beach ridge plain to a small sandy delta, off which there are shoals deposited from floodwaters in a sea that is stained red by suspended clay in the nearshore zone. Much of the impact of mining activities on the Dothio and the coastline adjacent to its mouth derives from the lower catchment. At present the river mouth is enclosed by a barrier spit that has grown northward from the Thio delta and become attached to the coast by deposition of sediment, mainly from the Dothio.

Nakéty

The lower part of the Nakéty catchment (area: 106 sq km) consists of ultrabasic massifs subject to extensive opencast nickel mining, and the delta has received an augmented yield of red clay, sand, and fine gravel. Comparison of 1954 and 1976 air photographs showed the growth of a littoral spit attached to the beach of St. Paul and the formation of an alluvial island, related to augmented sedimentation produced by mining activity from the late 1950s to the 1970s. Subsequently the beach ridge plain that borders the river mouth has been truncated by wave erosion, undermining some of the coconut trees that grew

PLATE 20. Mining Waste from the Thio Plateau Mine Spilling into the Upper Part of the Wellington Valley

PLATE 21. Opencast Mining on the Thio Plateau Has Triggered Landslides on Steep Hillslopes Bordering the Wellington Valley

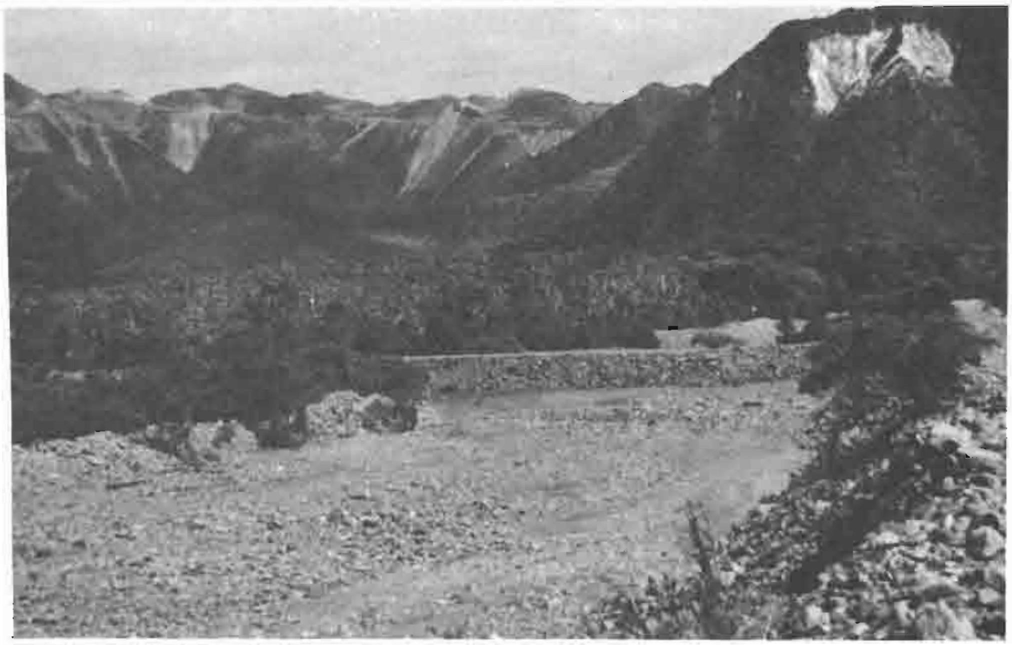

PLATE 22. The Wellington Valley, Showing Boulder Levees and a Dam Bulldozed to Confine the Watercourse and Diminish the Effects of the Next Phase of Floodwater Discharge

on the sandy terrain (plate 23). In general, beach erosion is unusual adjacent to the mouths of New Caledonian rivers that have sediment yields augmented by the effects of opencast mining, as river floods have generally supplied sufficient sand and gravel to maintain or prograde such beaches. It is possible that the beach erosion behind the Baie de Nakéty is a temporary phenomenon induced by the storm surge that accompanied Cyclone Gyan in December 1981, and that in due course material from sandy shoals off the river mouth will be carried shoreward by wave action to rebuild the eroded sector.

Canala

The Canala river system (catchment: 290 sq km) drains a mountainous area north of the Plateau de Dogny, within which Mesozoic sedimentary and volcanic rocks predominate. In the lower catchment, above Boakaine, there are areas of opencast nickel mining which have produced waste material spilling down slopes and into lateral valleys. However, as only this part of the drainage basin is in ultrabasic rocks, the effects on the Canala River have so far been moderate in the lower reaches; moreover, anti-pollution works have recently been introduced in the Boakaine area. Some downwashed red clay has been deposited in the extensive mangrove swamps that border the Canala delta, built into the head of the Baie de Canala, but the mangroves remain healthy and are advancing seawards as this accretion proceeds. Between 1954 and 1976 an alluvial islet in one of the distributaries grew from about 180 x 100 metres to about 260 x 120 metres as the result of mud accretion and mangrove spread.

Ouango

North-west of Canala, the Ouango drains a small but steep catchment (area: 16 sq km) on the eastern side of the Mé Aiu Plateau. Opencast mining was extensive in the headwater region in the 1960s and 1970s, and vast masses of sand and gravel have been spread across the valley floor in a wide fan (plate 24) that extends down to the delta, which is growing out into a branch of the Baie de Canala. The delta consists of lobes of sand and gravel bordered to seaward by wide red mudflats formed by the accumulation of downwashed ferruginous clay (plate 25). The effects of nickel mining on this valley and delta have been severe.

PLATE 23. Beach Erosion, Baie de Nakéty. Although not extensive in New Caledonia because many beaches have been augmented by the arrival of sand and gravel carried downstream from nickel mining regions, erosion here resulted from storm waves accompanying Cyclone Gyan in December 1981.

PLATE 24. The Ouango River Has Been Aggraded by the Deposition of Sand and Gravel from the Opencast Nickel Mine on the Mé Aiu Plateau

PLATE 25. Mining Waste Washed Down the Ouango Valley (plate 24) Has Been Carried into an Arm of the Baie de Canala, Producing a New Delta That Is Being Colonized by Scrub and Woodland Vegetation

Karoipa

The hilltop nickel mining that has discharged such large masses of waste material into the Ouango valley has also affected the Karoipa valley to the north. Although the catchment is small (area: 23 sq km), the river channel has been much widened, and a delta of sandy sediment, fringed seaward by red clay, is growing into the southern part of the Baie de Kouaoua (plate 26).

Kouaoua

The Kouaoua river basin, with its large tributary, the Kakenjou (combined catchment: 253 sq km), drains an area dominated by the ultrabasic massifs of Mé Aiu to the south and Ménazi to the west. In the latter, opencast hilltop nickel mining has been very extensive during the last 15 years. In 1981 the Ménazi massif was the chief mining centre in New Caledonia, the SLN mine producing 779,000 tonnes of ore and Pentecost Kouaoua a further 462,000 tonnes. In consequence, the Kouaoua and especially the Kakenjou have received substantial amounts of coarse sediment, their channels have widened, and deposition of sand and gravel is building up spits and bars in the deltaic region near Aoumou. The configuration of the coastline at the mouth of the Kouaoua has changed considerably in recent years, as shown on successive air photographs, and the present mouth is almost enclosed by a long curving sand spit, built up by wave action in the months since the floods generated by Cyclone Gyan washed out the previous bordering spits from the river mouth. Red-stained sea and offshore shoals in the Baie de Kouaoua off the river mouth are further indications of changes due to the impact of mining activity in the hinterland.

Koua

The Koua catchment (195 sq km) extends back to the crest of the Central Ranges, consisting of Palaeozoic and Mesozoic schists. The upper basin includes part of the peridotite Grand Massif du Sud, relatively wide in this region. The nickel deposits on the north slope of the Ménazi massif have been intensively mined for two decades, but the mines are more than 15 km inland and mining waste from this source has not yet extended far downstream. In the coastal regions there are areas of active and historical mining north of the river at a low level, and waste material from these has aggraded the channel, inducing bank erosion

PLATE 26. Tidal Flats Developing off the Mouth of the Karoipa River, Dominated by Red Clay Derived from Mining Waste in Its Upper Catchment. In the foreground the gravelly stream has received material eroded from the hillside in the course of road construction.

and meander displacement. Arrival of additional sediment at the river mouth has built up the delta, the bordering sandy beach having been widened and extended along the whole length of the delta shoreline between 1954 and 1976 as the result of augmented accretion.

Baie de Poro

The coastal peridotite massifs have here been subject to open-cast nickel mining by the Société Le Nickel. In 1981 this region was the fourth largest mineral producer in New Caledonia, but in 1982 mining ceased here. By then large quantities of red clay, sand, and gravel had moved directly down coastal slopes to the present shoreline. Much of the augmented sediment yield, however, is travelling to the sea by way of the overloaded Goua stream (catchment: 9 sq km), at the mouth of which sand and gravel are being washed into the sea. To the north, pisolitic ironstone sands and fine gravels have been carried down from coastal slopes to form a depositional terrace prograded on to the fringing coral reef that lines the coast up to Paraouyé (plate 27). Locally, the beach of dark sand has been cemented into layers of beach rock by calcium carbonate precipitation. The delivery of sand to this coast is evidently the outcome of prospecting and mining activities in the coast range during the past century, so that the beach rock must be of very recent origin.

Houaïlou

The Houaïlou and its tributaries, notably the Néaoua, drain an extensive basin (combined catchment: 539 sq km) north-east of the Col des Roussettes in the Central Ranges. In its headwaters the ultrabasic massif of Mé Maoya has been subject to opencast nickel mining, and some waste material has been carried downstream. Torrential runoff during Cyclone Gyan in December 1981 widened the river channel and carried masses of sand and gravel, including peridotite boulders, further downstream, with sediment of diminishing calibre extending still further. At the river mouth sandy material washed down during floods has been built by wave action into a chain of spits and barrier islands. In this deltaic region the Houaïlou is joined by the Néaoua River from the south, draining valleys cut into ultrabasic massifs that have been extensively mined for nickel. Red clay, silt, sand, and gravel are being carried by this river down to its confluence with the Houaïlou, so that coastal deposition has been

PLATE 27. Beach of Black Sand near Houaïlou, Produced by Longshore Accumulation of Pisolitic Ironstone Released from the Quarrying of the Laterite Capping on the Adjacent Hilltops

modified in recent decades by the effects of hinterland mining activity. Between 1954 and 1976 the delta shoreline was changed by the erosion of a wooded depositional island 250 metres long and 30 to 50 metres wide, and by the redistribution of derived sandy sediment by longshore drifting to prograde the coast to the north-east.

Ho

West of the ultrabasic plateau that forms the peninsula of Cap Bocage, the lower basin of the Ho River (catchment: 23 sq km) contains some opencast nickel mines, and pisolitic ironstone sands derived from the ferruginous lateritic crusts have been carried downstream and built by wave action into beach ridges bordering the river mouth in Baie Ugué. The effects of hinterland mining activity are only slight at the river mouth at this stage, but in the north-east of the Baie Ugué the fringing coral reef has been severely damaged by accumulation of waste of varying calibre from the Pounehoa mine on the Cap Bocage plateau, swept directly down the steep coastal slope into the sea.

Néavin and Monéo

The Néavin and Monéo rivers, with a combined catchment of 202 sq km, mark the northern limit of the ultrabasic Grand Massif du Sud on the east coast. The Néavin valley drains an area that has received some mining waste from hilltop excavations to the south, but the rest of the catchment is in strongly folded Mesozoic sedimentary and volcanic rocks which have not been mined. The impact of mining activities on this river system has therefore been minor. At and below the confluence of the Néavin and Monéo is a deltaic area with mangroves on shoals and a seaward fringe of spits and beach ridges built of grey sand and gravel, much of which has come from laterized ultrabasic hillsides in the coastal fringe. As with the Thio, the Kouaoua, and the Houaïlou, there have been marked changes in the last two decades in the configuration of spits bordering the river mouth, especially since these were washed through by floodwaters during Cyclones Alison and Gyan.

The North-Eastern Rivers

North of the Monéo the rivers of north-eastern New Caledonia drain catchments that do not contain large ultrabasic massifs and have only small outliers of overthrust peridotite. In sequence, with catchment areas in parentheses, the major rivers are the Mou, or Oué Pouémaeu (58 sq km), the Nimbaye (321 sq km), the Tchamba (187 sq km), the Amoa (182 sq km), the Hienghène (155 sq km), and the Ouaième (338 sq km). In their middle and lower reaches these rivers carry loads of generally grey sand and gravel, but at their mouths they are typically estuarine inlets or deep rias, in most cases with variable sand spits at the coast. The air photograph taken in 1976 of the Ouaième ria shows its mouth blocked by a sand barrier, but this was swept away by floods following subsequent cyclones, especially Cyclone Gyan in 1981 (which raised the river level 14.4 metres at the head of the inlet), and has subsequently been rebuilt as a cuspate foreland south of the river mouth.

The small Massif de Grandié, on the watershed between the Amoa and the Tiwaka, has not been subject to mining activity, and these rivers have not been affected by downwashed waste. The Massif de Tchingou, in the Tiwaka basin, has been prospected and mined on a small scale at two locations, and the small amount of mining waste has slightly affected some of the headwaters of this river. The upper basin of the Tipindjé includes two small peridotite overthrusts: the Oua Tilou massif, where mining activity has been very slight, and the small Massif de Poindas, subject recently to more intensive mining, which has so far led to waste pollution only in a few headstreams and in the upper reaches of the Tipindjé.

Conclusion

This review of the major river systems of the Grande Terre of New Caledonia has indicated the extent of impact of opencast mining on ultrabasic massifs in terms of changes on hillslopes, in valley floors, along river channels, on deltas, and in adjacent coastal areas. Figure 21 indicates the pattern of impact at river mouths around New

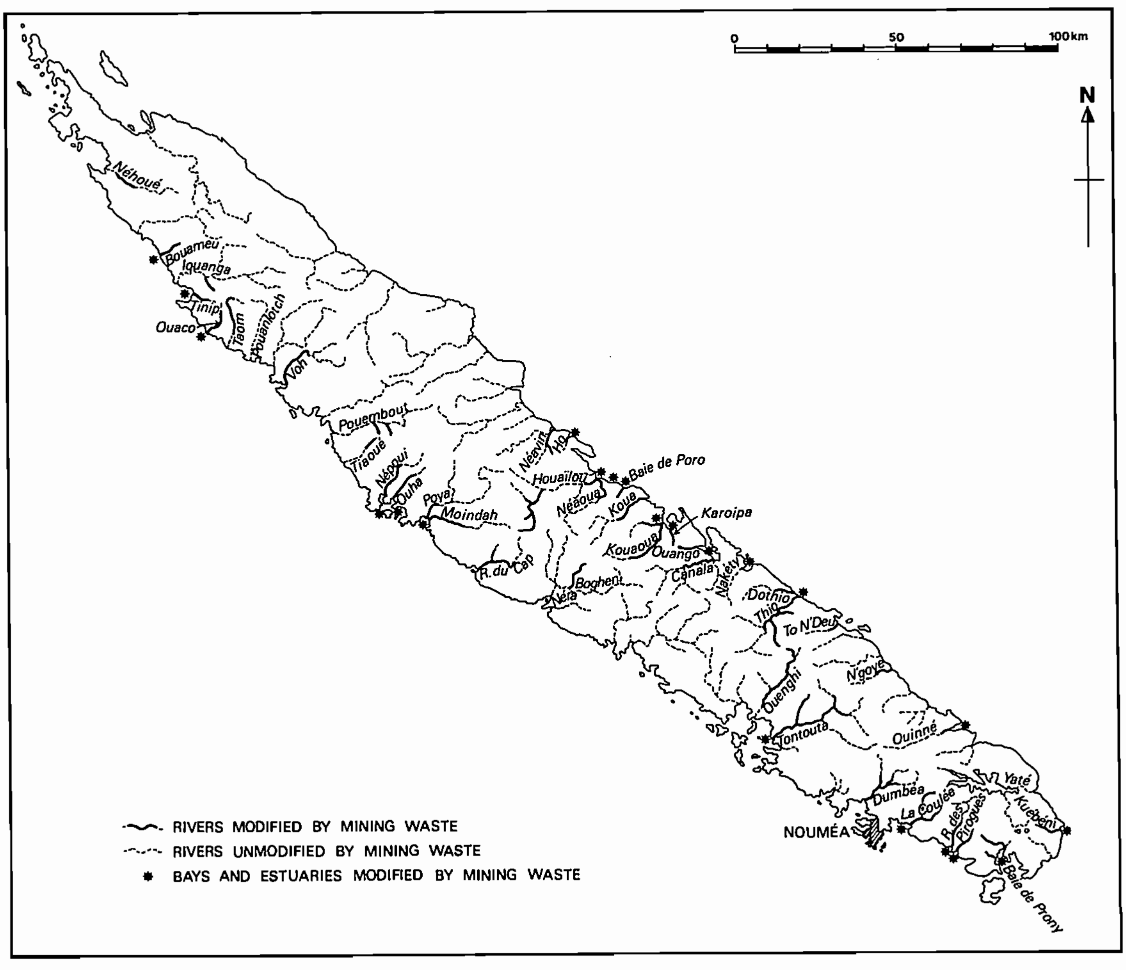

FIG. 21. Impact of Mining Waste on Rivers and Coastal Areas of New Caledonia

Caledonia. This impact has been severe on the Oué Bouameu, the Tinip, the Poué Koué, the Népoui, the Coulée, and the Rivière des Pirogues, on the west coast, and on a number of east coast rivers, notably the Ouango, the Karoipa, the Goua, and the Néaoua flowing into the Houaïlou. On a number of other rivers, notably the Pouembout, the Ouha, the Moindah, the Rivière du Cap, the Ouenghi, the Tontouta, the Dumbéa, and on the east coast the Ouinné, the Ngoye, the Thio, the Nakéty, the Canala, the Kouaoua, the Koua, and the Houaïlou, the effects are so far slight or moderate but may become more severe as waste from existing mines is added to the river system and as existing augmented channel loads move downstream. It is evident that opencast hilltop mining in the ultrabasic massifs of New Caledonia has profoundly modified upland areas and has had a spreading influence on the features of river channels, river mouths, and adjacent coastal environments.

The discharge of gravels to the mouth of the Koumac River, which drains a catchment unaffected by opencast mining, is an indication that a coarse-grained sediment yield is not necessarily the outcome of such mining. The rapid growth of the Comboui delta, on the east coast, is partly due to ravine erosion of hillslopes and partly to disturbance by mineral prospecting, yielding eroded sand and silt to the river mouth. Arrival of red clay and pisolitic ironstone sands at river mouths is probably the most reliable indicator of modifications due to opencast hilltop mining of the laterized mantles of ultrabasic massifs. While the effects of such mining are prominent in the landscapes of New Caledonia, it is likely that road-making and mineral prospecting have greatly augmented fluvial sediment yields, both in catchments affected by opencast mining and in those where no mining has taken place. Other factors such as clearing, burning, and grazing of the natural vegetation cover as well as cultivation in hilly country have accelerated runoff and increased the yields of sediment to New Caledonian rivers. Mention has been made of the existence, particularly on hill country inland from the central west coast, of abandoned cultivation terraces (*tarodières*), built by indigenous people in the pre-colonial era. The yields from such land management systems would have been mainly fine-grained (sand, silt, and clay), in contrast with the wider range of grain sizes (up to gravel, cobbles, and boulders) in the waste materials generated by opencast hilltop mining on deeply weathered ultrabasic formations during the past century.

4. MINING AND LANDSCAPE MANAGEMENT

It has thus become clear that the opencast hilltop mining of nickel and iron ores in New Caledonia has had a devastating effect on landscapes within and around the ultrabasic massifs and has modified river channels, estuaries, deltas, and some nearshore sea areas (fig. 21). Such effects are not unknown elsewhere in the world.

On the high island of Bougainville, in Papua New Guinea, for example, opencast copper mining has resulted in the discharge of about 150,000 tonnes of rock waste and tailings daily. The tailings have spilled down into a headwater valley of the Kawerong River and thence into the Jaba valley, where they have spread out across the valley floor, destroying large areas of rain forest and killing fish in the river. At its mouth the Jaba has built a new delta out into Empress Augusta Bay, and sand and gravel have been spread northwards along the shore as a prograded beach (Brown 1974). (It is likely that the mining of copper and gold from the mountainous headwater regions of the Ok Tedi, a tributary of the Fly River in western Papua, will generate waste material to augment the already large load of the Ok Tedi, and increase deposition on the Fly delta. But natural rates of sediment yield are here so high that the effects are not expected to be as drastic as on Bougainville or in New Caledonia [Jackson 1982].)

In the Philippines, iron ore mining has led to siltation and pollution of the Larap River on the island of Luzon, adversely affecting the fishery resources of that river and of Larap Bay off its mouth. The Lawis River, in western Luzon, has been similarly affected by chromite mining; the Taft River on Samar Island by iron ore extraction in its headwater regions; and the Abra River, also on Luzon, by gold, silver, and copper mining in its upper tributaries. In each case the river load has been augmented by the inflow of silt and sand (Rabanal and Datingaling 1973).

River channels have been greatly modified and their sediment loads increased by tin mining in various parts of Malaysia and Burma, and there are reports of similar impacts from the copper mines of Chile, Peru, Zaire, and Zambia. In Kelantan and Trengganu, provinces of Peninsular Malaysia, the mining of tin ore (cassiterite), gold, iron ore, and bauxite from hillside and valley-floor deposits has been in progress for over a century, and has resulted in extensive siltation and discoloration of such rivers as the Kinta, the Klang, the Semenyih, and the Pahang. Channel aggradation, levee accretion, increased flooding, and river diversion have been widespread; productive agricultural land has been buried by sand deposition; and villages have had to be relocated (Douglas 1967, 1970; AUSTEC 1974). Successive government acts have put restrictions on the more severely polluting mining activities, for example, "lampanning" — the hydraulic sluicing of hillsides for tin ore, which led to landslides and outwash fans and to accretion along valleys, much as in New Caledonia. Shoaling has occurred rapidly in the estuaries of Malaysian rivers that drain mining areas, damaging fisheries but increasing the tidal mudflat habitat for some shellfish such as cockles.

In south-west England the opencast extraction of kaolin (china clay) from the granitic uplands of Hensbarrow Down near St. Austell and from south-west Dartmoor has generated massive heaps of granular waste (mainly quartz and felspar gravels) and has polluted the adjacent rivers, which are white with suspended kaolin. In St. Austell Bay this white sediment discolours the blue waters of the English Channel to various shades of green.

The reddening of sea water by polluted rivers draining opencast mining areas in New Caledonia constitutes "aesthetic pollution" and may disturb and impoverish the flora and fauna of coastal waters, notably coral growth and fisheries. Locally, as in the Baie de Prony, it appears that some marine organisms have adapted to the modified environment. In most cases the deposition of red mud at river mouths has not impeded the growth and spread of mangroves, although these have suffered recurrent damage from discharging river floods. Red-staining of marine waters occurs in a number of places around the world, including streams flowing from the Redruth tin mines into St. Ives Bay, southwest England, and in localities on the coasts of Liberia.

In western Tasmania, sand and gravel washed from the Mount Lyell copper mines at Queenstown and from surrounding hillsides denuded of their forest cover by bushfires and toxic fumes from the smelter have passed into the headwaters of the King River.

The classic case of mining impacts on valley and coastal features was that generated by the sluicing of hilltops for gold extraction in the Sierra Nevada, in central California, in the nineteenth century (Gilbert 1917). After the discovery of gold-bearing deposits in 1848, jets of water were used to excavate quarries in gravelly material in the headwater regions of the Yubas, the Bear, and the American rivers, tributaries of the Sacramento River, which flows into San Francisco Bay. This procedure yielded vast quantities of sand, silt, and clay as well as pebbles, cobbles, and boulders to valley-side fans, and thence into the rivers. Valleys that had been deeply incised were aggraded: in the upper Yuba the valley floor was raised by up to 100 metres. With successive floods this detritus was carried downstream, and the major flood of 1862 swept large masses of sediment down to Sacramento and beyond, burying farmland, filling previously navigable river channels, and increasing the risk and scale of future flooding; sand and mud were deposited, shallowing the northern arms of San Francisco Bay. The resulting outcry led to the prohibition of sluicing by 1884, when miners were no longer allowed to cast their tailings into the streams. But the downstream dispersal of mining waste has continued, and the channels of the Yuba, bordered by dissected terraces dating from the mining phase, are still overloaded, with a gradation from coarse to fine channel sediment down the river. In all, some 1,816 million cubic metres of material (about eight times the volume removed to cut the Panama Canal) were excavated between 1849 and 1914 (non-hydraulic mining having continued after 1884), of which 675 million were still in the valleys, 224 million in the Sacramento delta area, and 914 million in San Francisco Bay and the adjacent sea.

Opencast mining in New Caledonia has been on a similar scale. Compared with other mining areas elsewhere in the world, the impact of opencast hilltop mining in New Caledonia has been exceptionally severe and extensive. Large areas have been desertified by the removal of weathered overburden from plateaux and hill crests, and by the spilling and slumping of waste material down hillsides and into neighbouring valleys. It is of course almost impossible to extract the nickel ores, which occur at the base of weathering mantles up to 30 metres deep on these summit plains, without conspicuous devastation; the only way would be to excavate a crater, leaving the rim intact, and working rotationally downwards through the overburden until the richest ores were encountered, although this would be very costly. Mining of superficial iron ores requires the removal of surface layers, but it would be fairly easy to shape the remaining material into a relatively stable landscape on which a soil and vegetation cover could be reestablished.

Unfortunately, natural regeneration of vegetation has been very poor in areas that have been mined and on the waste deposits, even where the latter have become relatively stable at low angles of rest. As has been noted in chapter 2, the rapid expansion of nickel mining in the boom years of the 1970s, when numerous mining companies obtained leases and proceeded to quarry almost every ultrabasic massif in New Caledonia, was followed by a steady fall in nickel prices, which led to the cessation of mining activities in many areas. Abandoned, the hilltop mines stand as stark, derelict, unvegetated landscapes, and the waste products spilling down their bordering slopes are easily mobilized, especially by the heavy downpours that accompany the passage of tropical cyclones. Although commendable attempts have been made in some areas (since the mid-1970s) to arrest downslope movement of mining waste by building rock dams, terraces, and settling basins to trap tailings and by impounding streams polluted by red clay in suspension, the movement of mining waste into rivers, and eventually to the sea, is bound to continue for many decades after mining comes to an end. The next phase of higher prices for nickel ores will certainly revive opencast mining in many areas that have recently been abandoned, and probably extend it into areas not yet mined. It has been suggested that the nickel reserves of New Caledonia (the richest known reserves in the world) will last for at least 200 years, so that the geomorphological and ecological effects of opencast hilltop mining are likely to persist for several centuries.

Some improvement can be expected with the wider application of the landscaping techniques devised by the Société Le Nickel and the smaller companies to reduce dispersal of mining wastes. The stabilization of mining waste and of eroding surfaces in and around mined areas could also be improved by the planting of vegetation. Natural regeneration of the indigenous maquis, scrub, and forest is very slow, but might be hastened by the planting of native species. Alternatively, afforestation with pine plantations (especially *Pinus caribaea* and *P.eliottii*) may prove to be an effective way of stabilizing and revegetating landscapes modified by opencast mining and mining waste (plate 28). Jaffré et al. (1977) have ascribed the poor regeneration of vegetation to the low mineral content and high porosity of surface materials left by opencast mining and waste deposition, as well as to the occasional presence of toxic chemicals in the soils. They advocated the planting of species found to be tolerant of these difficult edaphic conditions, for example, *Acacia spirorbis* on soils rich in magnesium compounds, and the application of soil improvement techniques (e.g., loosening of rocky surfaces, mulching, and addition of fertilizers such as phosphates) to facilitate plant growth. While it is possible that chemical compounds derived from mining waste are passing into solution in ground water and seeping into the rivers, no specific instances of adverse ecological effects of such chemical pollution have yet been identified.

New Caledonia is remote from centres of conservation activism, and the impacts of opencast hilltop mining have attracted much less criticism than they would have done in Europe, North America, or Africa, where it is likely that severe restrictions would have been placed on the nature and extent of such mining, with an insistence on more effective conservation works to minimize the effects of waste dispersal from mined areas.

PLATE 28. Experimental Work Carried Out on Areas Laid Bare by Opencast Mining of Nickel Ore in the Massif du Sud to Assess Rates of Runoff and Sediment Yield. Comparisons have been made with similar plots on which vegetation has been established; it is evident that a replanting programme could restore a vegetation cover to this mined landscape (cf.Jaffré et al. 1977).

In the 1970s a territorial commission for the prevention of damage by mining was established in New Caledonia, composed of representatives from public authorities, local agencies (municipal and Melanesian), mining companies, and scientific organizations. Thereafter, new mining necessitated an authorization from the Service des Mines following consultation with the commission, which is required to make a field inspection of the area to be mined, assessing the risks of erosion on and around the site and compiling a botanical inventory to check if there are rare species or communities requiring site preservation. If mining is authorized, the mining company is obliged to put in conservation works to prevent damage and pollution downslope and downstream from the mining area. These include slope terracing behind boulder walls to achieve soil and waste mantle stabilization (plate 29), barrages to intercept downwashed material (plate 30), and management to maintain percolation and prevent erosion along prospecting trackways and access roads. These procedures are helpful, but have been introduced far too late to prevent extensive damage. In particular, the many mines developed during the period of rapid expansion (1968–1973) and then abandoned are responsible for widespread and still uncontrolled erosion, waste dispersal down slopes, and river pollution and aggradation, the effects of which are still spreading and will persist for many decades, possibly centuries.

In recent years the New Caledonian Association pour la Sauvegarde de la Nature has endeavoured to promote an interest in nature conservation and landscape protection, especially in areas where there are still good stands of indigenous vegetation rich in endemic species, including *Araucaria* forests and varied maquis. Hilltop mining has been very widespread, and damage by roads and excavations built in the course of mineral prospecting still more so. But some areas with native vegetation remain, either on undisturbed rocky outcrops or on lateritic soils on the hill crests and slopes of ultrabasic massifs, and a few areas where the unusual geomorphological features of peridotitic karst still persist: for example, on the Mé Aiu plateau, north of Canala. The Association would like to see some of these preserved as territorial parks or nature reserves to stand as memorials of the native vegetation and original landscape, and as standards against which the changes wrought in and around mined areas can be assessed.

The problem of rehabilitating mined areas and associated deposits of mining waste may prove

PLATE 29. Boulder Walls Built along the Contour on the Southern Slopes of the Thio Plateau to Intercept Downwashed Mining Waste and Reduce the Amount Discharged into the River Valley

PLATE 30. Interception Dam Trapping Mining Waste Washed Down the Boakaine Valley near Canala on the East Coast of New Caledonia

more difficult and enduring than the recovery of river channels and coastal environments once mining comes to an end. In areas where mining ceased three or four decades ago (e.g., in the vicinity of Voh, on the west coast), river channels still contain coarse gravelly loads, but vegetation has revived on their banks and the conspicuous red clay has been washed away. At the coast, the fringes of deltas that received additional sediment during and after the phase of hilltop mining activity are becoming more stable as the outflow of sediment slackens and the red staining of sea water gradually fades as the ferruginous clay in suspension is either dispersed or coagulated and precipitated into sea floor sediments. In due course, the modern phase of deposition resulting from mining activity will come to an end and quieter sedimentation will ensue. It may eventually be difficult to distinguish the sediments formed by this anthropogenic deposition from those of earlier phases, when relatively widespread deposition of coarse piedmont deposits resulted from tectonic uplift in the hinterland or from climatic changes. At present, however, the impacts of opencast mining on the landscape of New Caledonia are conspicuous and extensive, and they are likely to remain so for a prolonged period. A long-term programme of stabilization and revegetation of the areas subjected to mining and deposition of sedimentary waste materials is now needed to rehabilitate the landscape ecosystems of this ravaged South Pacific island.

REFERENCES

Antheaume, B. 1981. "Extraction minière et métallurgie." *Atlas de la Nouvelle-Calédonie*, plate 41. ORSTOM, Paris.

AUSTEC. 1974. *Pahang River Basin Study*. Kuala Lumpur.

Balzer, F. 1965. "Le Marais de Mara." *Cahiers du Pacifique*, 7: 69–92.

——. 1969. "Les formations végétales associées au delta de la Dumbéa." *Cahiers ORSTOM, sér. Géol.*, 1: 59–84.

Bird, E.C.F. 1972. "The Origin of Beach Sediments on the North Queensland Coast." *Earth Sci. J.*, 5: 95–105.

——, and J.A. Iltis. 1983. "New Caledonia." In E.C.F. Bird and M.L. Schwartz, eds., *The World's Coastline*. In press.

Brown, M.J.F. 1974. "A Development Consequence — Disposal of Mining Waste on Bougainville, Papua New Guinea." *Geoforum*, 18: 19–27.

Chevalier, J.P. 1973. "Coral Reefs of New Caledonia." In O.A. Jones and R. Endean, eds., *Biology and Geology of Coral Reefs*, 1: 143–167.

Compton, R.H. 1917. "New Caledonia and the Isle of Pines," *Geogr. J.*, 49: 81–106.

Coudray, J. 1976. *Recherches sur le Néogène et le Quaternaire marin de la Nouvelle-Calédonie*. Fondation Singer-Polignac, Paris.

Davis, W.M. 1925. "Les côtes et les récifs coralliens de la Nouvelle-Calédonie." *Ann. de Géogr.*, 34: 244–269, 332–359, 422–441, 521–558.

Douglas, I. 1967. "Natural and Man-made Erosion in the Humid Tropics of Australia, Malaysia and Singapore." *Publ. Int. Assoc. Sci. Hydrol.* (Bern), 75: 17–30.

——. 1970. "Measurements of River Erosion in West Malaysia." *Malay. Nat. J.*, 23: 78–83.

Dugas, F. 1974. "La sédimentation en Baie de Saint-Vincent (Côte Ouest de la Nouvelle-Calédonie)." *Cahiers ORSTOM, sér. Géol.*, 6: 41–62.

Gilbert, G.K. 1917. *Hydraulic-Mining Debris in the Sierra Nevada*. U.S. Geol. Surv. Prof. Pap. 105.

Glasser, E. 1904. *Les richesses minérales de la Nouvelle-Calédonie*. Dunod, Paris.

Guilcher, A. 1963. "Quelques caractères des récifs-barrières et de leurs lagons." *Bull. Assoc. Géogr. Fr.*, 314 and 315: 2–16.

——. 1965. "Grand Récif Sud: Récifs et Lagon de Tuo." *Expédition Française sur les récifs coralliens de Nouvelle-Calédonie*, 1: 135–240.

Iltis, J.A. 1979. "Activité pastorale et dégradation: la région de Témala (Nouvelle-Calédonie)." *Photo-Interprétation*, 79–3: 23–26.

——. 1981. "Géomorphologie." *Atlas de la Nouvelle-Calédonie*, plate 13. ORSTOM, Paris.

Jackson, R.T. 1982. *Ok Tedi: The Pot of Gold*. University of Papua New Guinea, Port Moresby.

Jaffré, T., M. Latham, and M. Schmid. 1977. "Aspects de l'influence de l'extraction du minerai de nickel sur la végétation et les sols en Nouvelle-Calédonie." *Cahiers ORSTOM, sér. Biol.*, 12: 307–321.

Launay, J. 1972. "La sédimentation en Baie de Dumbéa (Côte Ouest — Nouvelle-Calédonie)." *Cahiers ORSTOM, ser. Géol.*, 4: 25–51.

——. 1982. *The Isle of Pines: Geological Background and Quaternary Sea Level Changes*. ORSTOM, Nouméa, New Caledonia.

Le Borgne, J. 1964. *Géographie de la Nouvelle-Calédonie et des Iles Loyauté*. Ministère de l'Education, Nouméa, New Caledonia.

Navunisaravi, N.B., and A. Rakanace. 1980. *Overseas Trade 1979*. Statistical Bulletin of the South Pacific, South Pacific Commission, 18.

Paris, J.P. 1981. *Géologie de la Nouvelle-Calédonie*. Mémoire B.R.G.M., Orléans.

Rabanal, H.R., and B.Y. Datingaling. 1973. "Problems of Pollution and Siltation from Mines in Some Philippine Waters." In A.B. Costin and R.H. Groves, eds., *Nature Conservation in the Pacific*, 263–270. Australian National University Press, Canberra.

Service de la Statistique. 1980. *Les comptes économiques*. Notes et Documents, no. 19. Nouméa, New Caledonia.

Service des Mines et de la Géologie. 1971–1981. *Rapports annuels*. Nouméa, New Caledonia.

Wirthmann, A. 1970. "Zur Geomorphologie der Peridotite auf Neukaledonien." *Tübingen Geographische Studien*, 34: 191–201.