Chapter 10

Mineral resources and prospectivity of the ultramafic rocks of New Caledonia

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Abstract: The main metallic mineral resources of New Caledonia are hosted by the obducted Peridotite Nappe. Ni, Co, Cr and the Pt group elements (PGEs) are specific to this ultramafic terrane. Cr, as podiform chromite in the uppermost mantle, is the only hypogene metal mined economically in the past. The largest chromitite deposits are located in the Lherzolite Tchibaghi Massif. Supergene Ni and Co deposits are concentrated by the tropical climate that has prevailed since the Miocene. New Caledonian lateritic Ni deposits account for 10% of the global Ni resources. Hydrous Mg silicate and oxide types coexist in a single deposit. A local genetic model based on geomorphological evolution is proposed. Sc is a prospective resource associated with these supergene deposits. The PGEs are a prospective resource associated with chromite, with potential in the hypogene, supergene and fluvio-littoral domains. Pt and Pd are the most significant elements. The transition zone between the upper mantle and crustal cumulates constitutes a regional Pt-Pd-enriched horizon. The concentrations are related to small disseminated chromite lenses in a pyroxene-rich lithology. The PGEs are concentrated in weathering profiles. The value of chromite-rich sands as placers or sand beach deposits might be enhanced by the occurrences of PGEs.

One of the most prominent units of New Caledonia geology is the Peridotite Nappe (Avias 1967; cf. Maurizot et al. 2020a, Chapter 5, this Memoir), a large ultramafic mantle sequence obducted at the end of the Eocene convergence cycle. It provided the country with a wealth of valuable mineral resources, including Ni, Co, Cr and Fe, and contains other prospective resources, such as the Pt group elements (PGEs) and Sc. The other mineral resources of the non-ultramafic units of New Caledonia are addressed in Maurizot et al. (2020b, Chapter 9, this Memoir), in which a general geological setting is also provided.

The Peridotite Nappe extends over 8000 km², 30% of the area of Grande Terre. It consists of a southern unit, the Massif du Sud, its extension along the northeastern coast and a number of tectonic klippe spread along the southwestern coast (Fig. 10.1). As a result of its late emplacement on top of the allochthonous terranes stacked over the Norfolk Ridge and its high relief, the Peridotite Nappe is topographically in a dominant position and constitutes most of the high landscape of New Caledonia. This ultramafic terrane is formed of upper mantle rocks, commonly harzburgite and dunite (Prinzhofer et al. 1981). Lherzolite is known in the north, in the Tiébaghi, Poum and Belep massifs (Moutte 1982). In the south of the Massif du Sud, the mantle sequence is overlain by a transitional dunite horizon, then by cumulates (pyroxenite, wehrlite and gabbro). Neither a crustal dyke complex nor pillow basalt is exposed over the crustal cumulates.

Ni, Co, Cr and the six PGEs are usually found at higher concentrations in mantle rocks, but only Cr as chromite and the PGEs as platinum group minerals (PGMs) are concentrated in the primary ultramafic protoliths as economically mineable hypogene ore bodies. The Peridotite Nappe has been subject to tropical weathering since the Miocene (cf. Sevin et al. 2020, Chapter 7, this Memoir). This long-term post-obduction supergene evolution has led to secondary surface concentrations. Ni and Co are the main relevant metals of these supergene deposits and represent the basis of New Caledonia’s economy. Fe and, to a lesser extent, Sc, Cr and the PGEs were also concentrated during these weathering episodes. Ultimately, resistant and dense minerals such as chromite and the PGMs have been, and are still, eroded and transported into the alluvial and littoral hydrosystems, feeding sedimentary deposits of potential economic interest.

New Caledonia’s mineral resources have been estimated repeatedly during its history at the initiative of government authorities. The first assessment of the natural resources of the country was conducted soon after colonization (Garnier 1867a, b, c) and led rapidly to the discovery of Ni deposits. Mining exploration, mainly of Ni, was allotted to private initiatives for more than a century. In the early 1980s, as a result of the drop in the price of Ni, the French Government launched a systematic mineral exploration programme with the aim of diversifying the mining industry. This Mineral Resources Survey programme was conducted by the French Bureau de Recherches Géologiques et Minières (BRGM) between 1980 and 1990. In the ultramafic rocks, it involved Cr and the PGEs, with the exception of Ni.

Curiously, scientific research on the geology of New Caledonia’s Ni deposits was not very active until the 2000s. This was a result of multiple factors, such as the abundance of the resource, easy opencast mining and the complexity of the geological controls. Only a few geologists were employed in mining companies and fewer again conducted research on Ni metallogeny. Moreover, most of the few scientific studies carried out by private companies operating in the country remained confidential. The growing global demand for Ni after the 1990s changed this situation and boosted scientific research. Since 2008, most of the research on Ni deposits has been funded by the Centre National de Recherche et de Technologie Nickel et son Environnement (www.cnrt.nc), an agency funded by the French State, local communities and mining companies.

Among the different resources addressed in this chapter, some are currently economically important (Ni and Co), some have been important in the past, but are no longer mined (Cr and Fe), and some have been actively explored and prospected as yet unsuccessfully (the PGEs), but have future potential. Some resources are newcomers and prospective and therefore require more exploration effort and research support (Sc). For the sake of logic and coherence, the different
mineral resources will be presented in chronological order of formation: hypogene, supergene and fluvio-littoral.

Information on many of these resources (e.g. Cr) is only documented in unpublished reports in the French language, most of them available in the archives of the New Caledonia Government administration department in charge of mines (DIMENC). Irrespective of their abundance or importance, all the known mineral occurrences, prospects and deposits are presented in this Memoir at their current state of knowledge and unpublished references are cited for the sake of completeness. Statistical data on production and grade have been collected from official (US Geological Survey and the New Caledonia Government) and non-official (consultancy and company reports) sources and were consolidated with unpublished literature. In this chapter, the mining terminology is used in compliance with the recommendations and guidelines of the Committee for Mineral Reserves International Reporting Standards. A mineral occurrence is a showing of any size that is of geological interest, but not necessarily of economic interest. A mineral deposit is a concentration of material, economic or not. A prospect is a mineral deposit on which some preliminary prospection or mining works have been carried out. A mineral resource is a concentration of material whether or not it is economically and technically feasible. A mineral reserve is the economically mineable part of the mineral resource.

**Hypogene deposits**

**Chromium**

About half of the world’s Cr production comes from podiform chromitites that occur in mantle peridotites (Thayer 1960, 1964), commonly hosted in the lithospheric portions of ophiolites (half of the world’s past production of Cr; Mosier et al. 2012). Another type of concentration is as small stratiform or banded chromitites associated with the PGEs and hosted in cumulate sequences (dunite and gabbros) of the lower crust.

Worldwide, podiform chromitites are associated with dunite in harzburgite or lherzolite. The deposits are irregular in shape with a limited lateral extent. It is difficult to predict their distribution in a peridotite mass. Chromite occurs as a disseminated mineral in peridotite. Bulk peridotites typically have Cr concentrations of c. 0.5–1 wt% Cr₂O₃ (Mosier et al.
2012), whereas economically viable chromite deposits must contain >30 wt% Cr₂O₃.

The Cr deposits of New Caledonia occur in the Peridotite Nappe (Avias 1967) and are mainly of the podiform chromitite type. An inventory of the chromite deposits in New Caledonia was conducted by Maurizot (1990). About 300 occurrences, prospects and old mines were documented (Fig. 10.2). This country has been an exceptional natural laboratory in which to improve our knowledge of podiform chromitite deposits and many concepts and models developed here are still referenced (Cassard 1980; Leblanc 1995; Leblanc and Nicolas 1992; Moutte 1979).

The production of chromite in New Caledonia began as early as 1880. Many of the prospects were initially opened in the weathered profiles of peridotites, where the chromite ore is residually enriched by olivine oxidation and removal, giving way to grades >50 wt% Cr₂O₃. However, once this rich and easy to operate part had been extracted, the need to go underground proved a much more difficult challenge and led to many mine abandonments and failures. New Caledonia was the world’s third largest producer of chromite from 1896 to 1912. There has been no production of chromite in New Caledonia since 1990 (Gouvernement de la Nouvelle-Calédonie 2008; Paris 1981). A total of 92 tenements have been historically allocated for chromite, most of which had expired by 2016. One single mine exceeded 3 000 000 t in production (Tiébaghi), four mines exceeded 100 000 t and only ten exceeded 10 000 t. The total historical production of chromite for New Caledonia is estimated at 3 760 000 t of ore at a grade >40 wt% Cr₂O₃. Although it forms only 2% of the whole area of ultramafic terranes, the Tiébaghi Massif has supplied >87% of Cr production (3 270 000 t) and hosted the four largest mines (Fig. 10.2c).

The podiform chromitites of New Caledonia are present in two distinct geographical areas corresponding to two ultramafic domains. The main chromite mines in the Tiébaghi Massif are located in the harzburgite–lherzolite transition zone (Moutte 1979, 1982). Many small chromitite occurrences are known in the other lherzolite klippes (Poum and Bélep) to the north (Sécher 1981) in the same lithological horizon (Fig. 10.2b). In the Massif du Sud, small deposits cluster either within harzburgite or in dunite (Cassard 1980; Cassard et al. 1981). The deposits are clearly grouped as a halo around and below cumulates (Fig. 10.2a). To the NW they form an

![Fig. 10.2. Chromitite deposits in parts of the Peridotite Nappe. (a) Many small-sized occurrences in the Massif du Sud are located around and below the dunite–gabbro cumulate crustal sequence. (b) Most of the important economic deposits have been exploited in the northern lherzolitic massifs (Tiébaghi and Poum). (c) Graph showing the annual production of chromite in New Caledonia since 1880.](http://mem.lyellcollection.org/Downloaded from http://mem.lyellcollection.org/)
alignment, the Humboldt corridor (Podvin 1983a, b, 1985; Podvin et al. 1985), in deeper mantle harzburgites that could correspond to the roots of the presently eroded north-westwards extension of the crustal cumulates. Other ultramafic units along the western coast and within the Central Chain are remarkably sterile in terms of primary chromite deposits.

The typical features of podiform chromite deposits (e.g. Mosier et al. 2012; González-Jiménez et al. 2014a, b) are present in the New Caledonia chromitites. They are briefly summarized here with an emphasis on the New Caledonian characteristics. The margins of the chromitite deposits are always dunitic and may be either concordant with, or crosscut, the lithological layering in the host peridotite. Chromitite pods often comprise rounded aggregated structures of chromite grains in an olivine background and occur in both nodular and orbicular forms. Their negative mirror image, where olivine aggregates are surrounded in a chromite background, is termed anti-nodular or anti-orbicular. These last structures, in which the olivine aggregates are surrounded by a network of disseminated to massive chromite, are generally referred to as a ‘chromite net and occluded silicate texture’ (Thayer 1964). Mutual indentations and flattening of the chromitite nodules suggest that deformation occurred in a plastic state.

Nodular structures are common in the New Caledonia chromitites, although the specific orbicular texture is only mentioned in the Tiébaghi Massif at the Alpha prospect (Moutte 1979, p. 31).

The chromitite pods and peridotite host rock share, to various degrees, the typical mantle fabric, a high-temperature deformation consisting of a planar foliation associated with dunite–harzburgite layering and a stretching lineation (Prinzhofer et al. 1980; Cassard et al. 1981). Chromite isoclinic synfoliation folds or mullions parallel to the stretching lineation are common. At a macroscopic scale, the penetrative mantle fabric is expressed in chromitite as pull-apart cracks, filled with silicates and orthogonal to the stretching direction.

**Tiébaghi deposits.** Mining on the Tiébaghi Massif (Tessarolo 2013) began with the discovery in 1877 of chromite-enriched blocks in the thick ferricrete at the NE edge of the plateau (Fig. 10.3). From 1902 to 1920 the ore was extracted in an open pit that reached 100 m depth and 200 m across at an altitude of 580 m. From 1927 to 1962 the ore was extracted underground, below the open pit, as deep as 200 m below
the surface. After an interruption of 20 years, extraction resumed in 1982. A new 1.2 km long access drift was opened from the NE flank of the massif at an altitude of 200 m to reach the base of the main ore body (the so-called 32 lens). Three new ore body lenses, without surface intersections, were discovered by underground exploration drifts from 1983 to 1985 (the 45, 55 and 89 lenses) and were subsequently mined. All operations ceased in 1990. Small, non-economic ore bodies have been intersected in drillcore down to the 0 level.

The Tiébaghi, Vieille Montagne, Morrachini and Bellacoscia mines form a group of ore bodies aligned parallel to the foliation and the well-developed layering of the ultrabasic host rock (Fig. 10.3a, b). The main chromite ore bodies are enclosed in a southwestwards-dipping transition zone between a harzburgite–dunite unit (NE footwall) and a diopside harzburgite unit (SW hanging wall). To the SW, this harzburgite is followed by spinel lherzolite and plagioclase lherzolite. The ore is always contained in a dunite envelope between 10 cm and several metres in thickness.

Where thoroughly explored and mined, the ore bodies and their dunite envelope are seen to be partly controlled by the stretching structures of the mantle host rock (Fig. 10.3c). The 32 and 45 lenses have a pronounced columnar shape, whereas the 55 and 89 lenses have a more flattened lens-like shape. The 32 lens is composed of several large columns, elliptical in section, 40–50 m in diameter and 100–300 m long (Moutte 1979, 1982). The axes of the columns plunge between 55 and 70° to the SE, parallel to the stretching lineation of the enclosing host rock. The main chromitite ore bodies are linked by thin disseminated chromitite layers within a dunite envelope. Details of the different exploitation levels show a number of fold-like structures. The thick ore columns of the 32 lens probably correspond to thickened hinges with their axes parallel to the stretching lineation and their axial plane parallel to the foliation, or to sheath folds, a structure seldom reported in chromitites (Kelemen and Dick 1995). The 55 and 89 lenses could be located in the hinge region of a synfoliation fold with its axes normal to the stretching lineation. Other chromitite occurrences in the Tiébaghi Massif, such as the Fantoche mine, display similar dispositions with steeply plunging fold axes of the chromitite deposits. The ore bodies are clearly offset by prominent NW–SE-striking faults associated with late felsic intrusive rocks. These faults have both reverse and transcurrent offsets of 10–40 m. Subordinate conjugate NE–SW faults are also present.

The ore is mainly massive in the core of the columns and nodular at the edge, close to the dunite envelope. The massive ore is formed by the aggregation and compaction of chromite nodules. Large poikiloblastic crystals, several centimetres wide, of a green chromiferous hornblende–pargasite are commonly present in the massive ore (Leblanc 1978; Johan and Augé 1986). This hydrous silicate displays exsolution features and syn-crystallization with chromite.

A total of 3.27 Mt of chromite has been extracted from the Tiébaghi mine. As a comparison, the Vieille Montagne, Morrachini and Bellacoscia mines produced only c. 30 000 t of ore. From a maximum of 56 wt% Cr2O3 in 1907, the ore grade decreased at the end of the 1980s to 30–45 wt% Cr2O3 (Table 10.1). During this period, it was enriched to >50% by a small concentration unit, mainly by a gravitational process. Different types of ore were produced in the 1980s: lumpy ore (12–100 mm), refractory ore (1–12 mm) and fine-grained sand (<1 mm).

**Table 10.1.** Chromite production and grades of the Tiébaghi mine from 1902 to 1990

<table>
<thead>
<tr>
<th>Year</th>
<th>Production (t)</th>
<th>Grade (wt% Cr2O3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1902–20</td>
<td>775 000</td>
<td>50–56</td>
</tr>
<tr>
<td>1927–62</td>
<td>1 325 000</td>
<td>50–56</td>
</tr>
<tr>
<td>1980–90</td>
<td>1 170 000</td>
<td>30–45% enriched by gravity process to 55%</td>
</tr>
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Chromite compositions and inclusions. Pargasite, Na-rich phlogopite and nepheline are present as inclusions in the Tiébaghi deposits as well as some of the Massif du Sud chromitite deposits. These hydrous phases indicate that volatiles probably played a part in the formation of the chromitites (Johan and Le Bel 1978; Johan et al. 1983; Johan 1986; Johan and Augé 1986; González-Jíménez et al. 2014a), although their importance is still debated.

The compositional range of the New Caledonia chromitites is typical of podiform chromite ores, with a wide variation of Cr/(Cr + Al), a slight variation in Mg/(Mg + Fe) and a low Ti content (Leblanc 1987). Two main compositional domains exist (Fig. 10.4). The deposits from the northern lherzolites are richer in Cr (c. 59 wt% Cr2O3) than those of the Massif du Sud (c. 53 wt% Cr2O3) and have a large variability in Cr and Al (e.g. the Poum lherzolite). The multiple stages of depletion and re-fertilization of the northern lherzolites (Ulrich et al. 2010) may account for this greater Cr variability. There is a continuous trend from the Massif du Sud chromitites hosted by harzburgite and the small stratiform PGE-enriched type chromitite concentrations located in the dunite–gabbroic cumulate section of the Massif du Sud. This difference in composition shows the specificity of each area.

**Genetic model.** Although there is a profusion of genetic models for podiform chromitites (for a review, see González-Jíménez et al. 2014b) based on their geochemical
composition, structural features and geodynamic context, their
genesis is generally ascribed to magmatic crystallization and
segregation under uppermost mantle conditions. Two tectonic
settings are commonly invoked: (1) convergent margins, such as
island arc, back-arc or supra-subduction zone settings (Arai
and Yurimoto 1995; Arai 1997; Schiano et al. 1997; Ballhaus
1998; Matveev and Ballhaus 2002; Matsumoto and Tomuro-
goo 2003; Büch 2004; Rollinson and Adetunji 2013;
Shafai Moghadam et al. 2013); and (2) spreading mid-
ceanic ridges (Dickey 1975; Nicolas 1989; Leblanc
The chromitite occurrences in the Peridotite Nappe form two
clusters corresponding to two different mantle protolith com-
positions and therefore probably two tectonic settings: (1) in
the Massif du Sud, typical depleted harzburgites of the Perido-
tite Nappe are overlain by transitional dunites and crustal
cumulates and a number of small deposits (<100 000 t), less
rich in Cr, are located at or below this transitional zone; and
(2) the northern massifs of Tiébaghi, Poum and Bélep contain
important volumes of lherzolite associated with harzburgite.
The Tiébaghi Massif hosts the most important deposits in
term of volume (several Mt) and Cr content. The deposits
are located at the lherzolite–harzburgite contacts. Between
these two domains, the peridotites along the east and west
coasts are remarkably barren of any significant chromite
deposits.
A local structural interpretation of the Massif du Sud depos-
its, based on 50 occurrences and their relationship with the
host mantle and its deformation, has been proposed (Cassard
et al. 1981). According to this interpretation, the discordant-
type chromitites are formed as channelled dykes beneath and
close to the spreading ridge. They are gradually converted to
concordant-type chromitites (sills) via deformation, off
that centre, by progressive transposition and stretching in the
flowing mantle. Similar structural studies have not been
made of the northern chromitites.
The Peridotite Nappe protolith is generally considered to
have formed in a supra-subduction zone context (Aitchison
et al. 1995; Cluzel et al. 2001; Pirard et al. 2013) and resulted
from multiple stages of melting and re-fertilization (Ulrich
et al. 2010) during the evolution of the South Loyalty Basin
from pre-Paleocene spreading to post-Paleocene convergence.
Supra-subduction zone ophiolites are known to be hosts for
the world’s largest chromitite deposits (González-Jiménez
et al. 2014b). The occurrence of the largest chromite deposits
in lherzolitic protoliths of Tiébaghi strongly suggest a causal
relationship.

Prospectivity. The exploration and exploitation of Cr in New
Caledonia is dependent on the global market. Podiform chro-
mitite prospecting will always be a challenge as a result of the
random distribution of the occurrences, their unpredictable
and complex geometries, and the absence of any specific geo-
chemical or mineral haloes. Geophysical methods such as gra-
vimetry or electromagnetometry have proved to be of little
value due to the weak contrasts between the ores and the
host rock. Careful analysis of structural indicators, such as
follations and lineations, can be used successfully to determine
the direction of extension of outcropping deposits. Extensive
drilling remains the only solution to evaluating a prospect,
but the probability of intercepting a pencil- or column-shaped
ore body with a single drill hole (i.e. the likelihood of the two
lines intersecting) at depth is very low.

Platinum group elements
Most of world resources of the PGEs are hosted in ultramafic
stratiform layered complexes in ancient cratonic areas. Very
few economic occurrences of the PGEs are exploited in Phan-
erozoic ophiolites similar to the Peridotite Nappe of New Cal-
edonia; these are reputedly unfavourable environments.
However, the price of some PGEs has shown steady growth
since the 1990s and the PGEs are now on the European Union’s list of critical elements (Anonymous 2014). The
growing strategic value of these elements, and the fact that
they are produced by essentially only two countries (Russia
and South Africa), shows the need to look for other sources of
supply, in particular those in new metallogenic settings.
From this perspective, exploration for the PGEs was actively
promoted in New Caledonia in the framework of the Mineral
Resources Survey programme from 1990 to 2002. This green-
field exploration programme involved systematic sampling
and the geochemical analysis of stream sediments, alluvial
concentrates, rocks and weathering profiles in different parts
of the Peridotite Nappe. Although the occurrences discovered
are of modest size and are not yet economic targets, they pro-
vided a wealth of knowledge and scientific advances (Mauri-
zot et al. 1991; Augé and Legendre 1994; Augé et al. 1995b;
Maurizot and Augé 1995; Augé and Maurizot 2003;
González-Jiménez et al. 2011).
Pt was first reported in New Caledonia in 1891 (Pelatan
1891) and 1904 (Glasser 1904) as flakes in the sands of the
Andame River, a tributary of the Diahot River in the north
of New Caledonia. However, a geochemical stream sediment
and alluvial concentrate survey in the 1990s did not confirm
the presence of ultramafic rocks in the catchment of this
In a first stage of exploration (Maurizot 1991), the late intru-
sive rocks of the Saint-Louis and Koum granites (cf. Maurizot
et al. 2020c, Chapter 5) were surveyed on the assumption that
the PGEs could have been remobilized in their environments.
This idea was supported by the discovery of a millimetre-sized
 nugget of osmiridium reported in an alluvial concentrate of the
environment of the Koum granite (BRGM 1990). Although
this occurrence was reliable, further assaying of different sam-
ple from this area did not provide any significant PGE content
and this hypothesis was abandoned. Other targets tested for
the PGEs include sulphide occurrences in the peridotites, podi-
form chromitites and the transitional zone of the mantle to crust
sequence exposed in the south of the Massif du Sud (Fig. 10.5).

Peridotite Nappe sulphides. Primary base metal sulphides or base
metal alloys are present in trace amounts in the Peridotite
Nappe and their presence has been recorded since the early
twentieth century (Glasser 1904). These minor and very
restricted occurrences are constrained to the mantle sequence
of the Massif du Sud and its east coast extension (Picot
1959; Randoir 1967; Guillou 1969, 1972, 1973; Saos
1972; Guillou and Lawrence 1973). The sulfides are localized preferentially in pyroxene-enriched horizons defining the banding of harz-
burgite. Concentrations of sulphides may reach to 1–5%. The
mineral phases are haedlewoodite, pentlandite, awaruite, mil-
lerite and native Cu (Augé et al. 1999). At the mineral scale,
uncommonly high concentrations of PGEs may reach 13–
14 ppm for Pt and Pd and 1.5 ppm for Rh and Ir. The minerals
are of magmatic origin, with secondary transformations that
are probably related to serpentinitization. The scarcity of base
metal sulphides in the Peridotite Nappe makes these occurrences
unattractive from an economic viewpoint.

Podiform mantle chromitites. The presence of the PGEs
within chromite grains of ophiolitic mantle-derived chromi-
tites is well established (Constantinides et al. 1980; Page
et al. 1982; Augé 1985; González-Jiménez et al. 2014a). Podi-
form chromitites from the Peridotite Nappe are typically
enriched in Os, Ir and Ru, the refractory or Ir group PGEs,
which take the form of alloys (osmiridium, ruthenosmiridium) and sulfides (laurite, erlichmanite, xingzhongite and Ir–Cu sulfides) (Johan and Augé 1986; Legendre and Augé 1986; Augé 1988) and are strongly depleted in Pt and Pd. The absence of carrier minerals for Pt, Pd and Rh is characteristic of this type of environment. However, the bulk rock grade of the PGEs in podiform chromitites remains low (0.3–1.7 ppm for six PGEs; Augé and Maurizot 1992) and does not constitute an economic interest at present.

Chromitites in the mantle–crust transition zone. In the south of the Massif du Sud, the transition zone between upper mantle harzburgites and lower crustal cumulates constitutes a regional Pt–Pd-enriched horizon. The background contents of the different lithological members of the ophiolite (Picard 1995a, b; Augé and Maurizot 2002) are summarized in Figure 10.5. Stream sediment samples and alluvial concentrates, which are chiefly made up of laterite and chromite grains, bear inclusions of the PGMs. As a consequence, the PGE (mainly Pt–Pd) geochemical signal of the stream sediments is systematically enhanced and confirms regional geochemical surveys as an efficient method for this type of greenfield exploration for the PGEs.

Within this first-order lithological control, local PGE enrichments were found in small schlieren or lenses, commonly associated with pyroxene-rich lithologies, of disseminated chromite. The chromite contains inclusions of Pt–Pd-rich PGMs. The larger massive chromitite pods are not enriched in Pt–Pd.

Rivière des Pirogues prospect. A single value of 900 ppb Pt in a stream sediment led to the discovery of the mineralization of the Rivière des Pirogues in the Massif du Sud. Detailed mapping of the area and sampling of the different rock types enabled the anomaly to be traced back to the primary mineralization (Maurizot et al. 1991; Maurizot 1992b; Augé et al. 1995b). The mineralized area (1500 × 600 m; Fig. 10.6) corresponds to a massive dunite unit grading upwards successively into wehrlite, harzburgite, lherzolite and pyroxenite (orthopyroxene, clinopyroxenite and websterite). These rocks are cut across by a dense system of composite dykes consisting of wehrlite, pyroxenite (orthopyroxene-dominated) and gabbro up to 10 m thick. The pyroxenite dykes may have diffuse or sharp contacts with the wall rocks. In many cases they display several generations of infill and extensional structures. The gabbro dykes can be both separate and in the core of the pyroxenite dykes. They are often intensely deformed, displaying a
mylonitic foliation. A variety of cumulus textures have been observed in the different rock types (wall rock and dykes), including coarse-grained adcumulate in dunite or pyroxenite and heteradcumulate in wehrlite, with chromite and olivine as the cumulus phases. The composition of the minerals forming dykes (pyroxenes, olivine and disseminated chromite) overlaps that of the country rock, suggesting that they are co-genetic (Augé et al. 1995b).

Small chromite clusters enriched in Pt and Pd have been observed in the dunite and wehrlite cumulates and in pyroxenite dykes (Fig. 10.6a). In dunite and wehrlite they appear as thin schlieren and layers, 1–10 cm thick and a metre or so long. Chromite appears in cumulate texture associations (adcumulate or heteradcumulate) characterized by euhedral grains. The euhedral chromite crystals in pyroxenites are poikilitically enveloped in pyroxene.

All the chromite-rich rocks show Pt enrichment. The Pt content varies considerably from 500 ppb up to a maximum of 36.5 ppm (Fig. 10.6b). In places, channel sampling over 10 m provided an average content of 1 ppm Pt (Maurizot 1993). Pt is the most abundant PGE and is directly correlated with the Cr$_2$O$_3$ content, indicating that the Pt carriers and chromite crystals are co-genetic. PGMs occur as inclusions (1–200 µm) within the chromite crystals. The Pd content of the same chromite-rich rocks remains relatively low (maximum 770 ppb) and is roughly correlated with the Pt content. The main source of Pt in the chromitite appears to be Pt–Fe alloys and Pt sulfides and oxides. Os–Ir–Ru alloys, which are the
most common PGMs in podiform chromitite from the mantle sequence, are remarkably absent.

The Rivière des Pirogues area probably corresponds to part of a magma chamber, close to a feeder zone. The composition of the PGE-bearing rocks suggests that they could have been derived from an S-free and Cr–Mg–Ni-rich magma of possible boninitic affinity, a parental magma known as favourable for concentrations of Cr and the PGEs (Crawford et al. 1989). The dyke–host rock relationships suggest that coalescing residual liquids were collected from an incompletely crystallized system that could correspond to the context of a spreading zone. The instability, a parental magma known as favourable for concentrations of Cr and the PGEs (Crawford et al. 1989). The dyke–host rock relationships suggest that coalescing residual liquids were collected from an incompletely crystallized

Conclusions. Although as yet non-economic, there is diverse, abundant and unconventional chromite–Pt mineralization of the mantle–crust transition zone in the New Caledonia Peridotite Nappe. This suggests that the ophiolites might be reinterpreted for their potential in PGE enrichment and might constitute potential targets for further exploration for the PGEs.

Supergene deposits

Nickel

The history and economy of New Caledonia are inseparable from the Ni mining industry. Ni has provided the country with a considerable source of income since the second half of the nineteenth century and therefore plays a vital part in the current and future development of the country.

Two main types of Ni deposits are known worldwide (Freyssinet et al. 2005; Mudd 2010; Mudd and Jowitt 2014). Primary (hypogene) Ni sulfide deposits are found as lodes or layers derived from magmatic sources in ancient cratonic areas. Ni laterite (supergene) deposits are formed by the surficial weathering of ultramafic (mainly ophiolitic) rocks. In this last type of deposit, Ni and Co, which are trace elements in the parent peridotites (but above their average concentrations in the Earth’s crust) are further concentrated in the weathering profile. Being highly sensitive to erosion, most of the preserved Ni laterite deposits are geologically young (Neogene to present) and, as such, occur mainly in the tropics, although some older Ni laterite deposits are known at higher latitudes (Berger et al. 2011). The Ni laterite deposits are typically low grade and large tonnage. The surface conditions result in a resource that is easy to extract in open-cast operations. However, the mining of these deposits can be challenging because of their complex mineralogy and heterogeneous concentrations. Three main kinds of lateritic Ni ore types have been identified (Golightly 1979, 1981, 2010; Brand et al. 1998; Freyssinet et al. 2005; Butt and Cluzel 2013).

1. Oxide deposits (also mistakenly called lateritic), dominated by Fe oxy-hydroxides such as goethite. The ore grade is lower or equal to 2 wt% Ni with up to 0.3 wt% recoverable Co.

2. Hydrous Mg silicate deposits (also called saprolitic or garnieritic or silicate), dominated by Mg–Ni tectonite-like and smectite minerals, collectively referred to as ‘garnierite’. The ore grade is commonly > 2 wt% Ni with very low Co.

3. Smectitic or ‘clay silicate’ deposits, dominated by Ni-bearing swelling clays. The ore grade is in the same range as the oxide deposits, but with variable Co.

The Ni deposits of New Caledonia correspond to the generic laterite supergene type. Oxide and hydrous Mg silicate ore are dominant, whereas the clay type is very subordinate.

History. Nickel mineralization was first identified in New Caledonia in the Dumbéa River in 1864 by the engineer Jules Garnier, who was in charge of assessing the mineral resources of the French colony (Garnier 1867a, b). Later on, the distinctive grass-green coloured Ni-bearing mineral was named garnierite in the honour of its discoverer (Dana 1872). The first mining tenement for Ni in New Caledonia was granted in 1873 and the first mining operations began in the same year in the area of Mont Dore, followed in 1874 by Nakéty-Canala (Black 2014). Smelters were built in Nouméa in 1877 and Thio in 1880 and New Caledonia quickly rose to become the world’s largest producer of Ni (Howard-White 1963; Habashi 2009; Black 2014). In these early times, high-grade hydrous Mg silicate ore (garnierite; 10–15 wt% Ni) was hand-mined from veins and cracks in the saprock, in small quarries or even adits, following rich Ni lodes in deposits with reduced overburdens. However, in 1886, the New Caledonian mines were affected by the discovery of the Sudbury Ni–Cu sulfide deposit in Canada, which became the world’s leading producer of Ni until the middle of the twentieth century (Mudd and Jowitt 2014). In New Caledonia, the rich ores of the earliest mines rapidly declined to 5 wt% Ni by 1909. New Caledonian production continued at a modest scale of c. 5–10 kt Ni a−1. From 1900 to 1950, Ni production in New Caledonia was driven mainly by military demand from western countries, with peak production before the First and Second World Wars. More peaceful demands prevailed after 1950 (Golightly 1979).

The Doniambo pyrometallurgic plant of the Société le Nickel (SLN, a subsidiary of Eramet, the world’s first and the oldest continuously operating Ni company, if not the major one) was first built in 1910 in Nouméa using blast furnace technology. It gradually evolved in technology and scale and converted to the current rotary kiln electric furnace technology in 1958. The number and scale of Ni laterite projects in New Caledonia grew from the 1950s onwards. Operations began at larger scales in open-cast mines with mechanical extraction. There was increasing tonnage, decreasing grades and a growing sterile dump and stripping ratio. The New Caledonian Ni industry experienced a boom phase between 1967 and 1975 as a result of high global demands. During this period, permissive regulations led to major environmental
damage, which is still visible in the landscape, despite subsequent restoration efforts. This prosperous period was followed by a deep depression in Ni demand in the 1980s resulting from the global crisis in oil and raw materials.

The global production of Ni during the second half of the twentieth century and in the early twenty-first century was marked by the emergence of major new producers and competition with Russian (Norilsk) and Australian sulfide ores and other laterite producers (Mudd 2010). By the end of the 1990s, major technical improvements and a growing global demand resulted in drastic changes in the global Ni industry. New projects based on the hydrometallurgical process for low-grade oxide ores were developed in Western Australia, although the first hydrometallurgical process on low-grade oxide ore was performed in Cuba in 1959 and its technical feasibility was demonstrated during the same period in New Caledonia (Avias 1978). In New Caledonia, low-grade oxide ores took an increasing role in production for exports, even though this resource was not historically exploited, being at worst wasted or at best stockpiled.
A new mining regulation, promulgated in 2008, promoted the recovery and processing of ores within the country and imposed stronger constraints to preserve the environment (Gouvernement de la Nouvelle-Calédonie 2008). In the early 2000s, two world-class projects combining large mining sites and metallurgical plants were launched in New Caledonia by major Ni mining companies. The first project, to exploit the low-grade oxide-type ore of the Goro deposit, saw the opening by Vale (previously Inco) of a new hydrometallurgical plant in the northern province. In the second project, which was based on the exploitation of hydrous Mg silicate ores of the Koniambo Massif, a new pyrometallurgical plant using the nickel smelting technology process was launched by KNS or Koniambo Nickel SAS (Société Minière du Sud Pacifique SMSF) – Glencore (previously Xstrata, previously Falconbridge) in the northern province.

**Economy.** The current increase in the exploitation of larger tonnage and lower grade Ni deposits follows a historical and global trend. New Caledonia does not escape this pattern. Today, the main Ni projects in New Caledonia are based on resources of c. 100 Mt of ore from an area >100 km². Each of the three metallurgical plants running in the country has a full capacity of c. 60 000 t a⁻¹ of Ni contained. The Goro (oxide-type) and Koniambo (hydrous Mg silicate) deposits are among the top ten ranked projects worldwide by contained Ni.

Among the major Ni-producing countries, New Caledonia is probably the smallest in terms of surface and population (18 000 km², 270 000 inhabitants; ISEE 2014). A few data highlight the importance of the Ni industry in New Caledonia.

In 2014, the New Caledonian mining production was 13.1 Mt of ore (c. 60% hydrous Mg silicate-type ore at a grade of 2–2.2 wt% Ni and 40% oxide-type ore at 1.5 wt% Ni). The exported part of ore from 2000 to 2014 increased from 3 to 5.4 Mt a⁻¹ (50–40% of the total production, composed of c. 50% hydrous Mg silicate v. 50% oxide). The export grade is regulated and limited by the government to 2.15 wt% Ni (in 2014) to preserve the country’s resource (Fig. 10.8).

For a global annual production of 1 Mt Ni metal contained in 2000, reaching 2.2 Mt and over in 2013, all types, New Caledonia production accounts during the same period for 127 000 to 178 000 t, which represents a contribution of 13 to 8% of the world’s production (New Caledonia Government source; USGS 2011a, b). For the same period, New Caledonia ranks fourth to sixth for Ni contained production, all types. A total of 60% of the world’s ferronickel is produced from New Caledonia’s Ni ores (USGS 2014a). Ni production accounts for 7–10% of the country’s gross domestic product and is responsible for as much as 80% of foreign earnings. Ni ore and the derived metallurgical products represent c. 97% of the total value of the country exports (ISEE 2014). The global and locally available resources and reserves of Ni and Co are given in Table 10.2. The resource v. grade binary diagram of the world Ni laterite mines (Fig. 10.7c) shows the high grade of the deposits exploited by SLN and the large volume of developing New Caledonian projects.

**Ni–Co concentrations, terminology, processes and products.** The development of regolith in New Caledonia (cf. Sevin et al. 2020, Chapter 7, this Memoir) is beyond the scope of this chapter. Only the significant features related to the ultramafic protolith and Ni deposits are presented here.

When mining operations started in the late nineteenth century, the Ni mineralization was considered to be hydrothermal and of the lode type (Garnier 1867b; Avias 1978). Subsequent work (Glasser 1904; de Chételat 1947) considered the deposits to be supergene, a concept widely accepted today and...

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Fig. 10.8. Peridotite massifs, main Ni active mining sites, ore production (2014), coastal maritime transport, exported production (2013) and metallurgical plants (source Government of New Caledonia). The proportions of hydrous Mg silicate v. oxide ores extracted in the different mines do not only reflect the types of deposit, but also the economic choices and regulations.
Table 10.2. Global and local resources and reserves of Ni and Co in Mt of metal contained

<table>
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<th>Global all type</th>
<th>Global laterite type</th>
<th>New Caledonia</th>
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<tr>
<td>Resource</td>
<td>Ni</td>
<td>Co</td>
<td>Ni</td>
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<tr>
<td>Resource</td>
<td>300</td>
<td>7.2</td>
<td>80</td>
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<tr>
<td>Resource</td>
<td>178</td>
<td>12</td>
<td>47</td>
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<tr>
<td>Resource</td>
<td>15</td>
<td>0.86</td>
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Resources are inferred sensu the Committee for Mineral Reserves International Reporting Standards or as a “reserve base” sensu the US Geological Survey (Co, Mudd et al. 2013; Ni, Mudd and Jowitt 2014).  

sometimes referred to as the per descensum model (Cathelineau et al. 2016). Weathering, which, in turn, depends on the climate, is the most fundamental process in the formation of Ni–Co laterite deposits. Tropical climate conditions appeared in New Caledonia as early as the Late Oligocene (25 Ma) and still prevail today, despite global cooling during the Holocene (Sevin et al. 2012). The Ni lateritic deposits therefore result from a long, probably multiphase and certainly complex, evolution.

There is considerable variation, and therefore confusion, in the terminology used by different schools of thought, nationalities and specialists (geologists, mining geologists, mineralogists, regolith specialists, pedologists, geomorphologists and metallurgists) to describe and identify various levels of the weathering profile. Some of the common nomenclature and correspondences are given in Figure 10.9. This illustrates one of the main gaps between the main interpretations of knowledge on the supergene Ni deposits: many disciplines are involved that have different scales of study and aims. In this chapter we use laterite sensu stricto as a generic term for the whole weathering profile and laterite sensu lato for that part of the profile located between saprolite and ferricrete.

The development of Ni laterite sensu lato deposits is controlled by the interplay between a number of related geological and environmental factors. The main relevant and independent factors are represented in Figure 10.10. The internal factors are the parent lithology and the structure of the protolith. The external or forcing factors are the climate and tectonics (i.e. long-term, large-scale deformation). This results in a complex series of interactions between the solid (lithosphere) and liquid-gaseous (hydrosphere–atmosphere) envelopes of the Earth (Taylor and Eggleton 2001). The biosphere, which is probably an important factor in weathering processes, is not taken into account in this sketch.

An ultramafic substrate is a necessary condition for a concentration of Ni to form. However, the lithological variations (dunite, harzburgite, pyroxenite and lherzolite) probably do not play an important part on a large scale. Under tropical climates, ultramafic rocks contain more reactive and soluble minerals than other lithologies (Thomas 1994) and generally develop a thick laterite cover. The thickness of bedrock necessary to produce 1 m of laterite sensu lato varies from 1 m in saprock to 6 m in laterite sensu stricto (Fritsch et al. 2014). The reported rates of weathering are in the range 50–100 m Ma⁻¹ (Trescases 1973; Nahon and Tardy 1992; Freyssinet and Farah 2000; Freyssinet et al. 2005). A 50 m thick lateritic profile may therefore accumulate in 1–5 Ma under steady-state conditions without erosion and may represent up to 300 m of transformed bedrock.

Weathering smooths and subdues ultramafic landforms, which tend towards increasingly flat forms. The downwards progression of the weathering front tends to isolate individual cells or basins, often endorheic (hydrologically closed), covered by thick laterite and surrounded by residual ridges. Most of the weathering profile and bedrock is in the saturated zone. The water table surface is visible in many sinkholes, lakes and swamps. Sinkholes, elongated and aligned, attest to underground drainage and karst-like systems and are often unrelated to any surface networks. Such a landscape, exemplified by most of the basins in the south of the Massif du Sud, is probably the initial stage of formation of thick lateritic units and the associated Ni deposits (Genna et al. 2005a,b; Trescases 1975). Further relative sea-level variations (tectonic or eustatic) may change this basic configuration. Basins are inverted to plateaus, then then plateaus are eroded to more or less dissected mountains. Weathering is a complex process driven by a fluid (meteoric water) and includes chemical reactions (e.g. the leaching, discharge and precipitation of neoformed minerals) and mechanical processes (e.g. compaction, collapse and the underground transport of particles). In the ultramafic protolith, pervasive weathering leaches most of the soluble elements (e.g. Mg, Ca and Si) and leaves the less soluble elements (e.g. Fe, Al and, to some extent, Mn) to accumulate in situ. This subtractive process leaves a strong residual accumulation constituting the laterite profile. Very few clay minerals form as a result of the low AI content of peridotite, in which AI is essentially present in Cr spinel, a very weather-resistant mineral. Therefore the bulk of the laterite profile consists of dominant Fe oxyhydroxides. Ni, Co and Cr are also residually concentrated. Ni is c. 0.3 wt% and Co is c. 0.01 wt% in unweathered peridotite. In the laterite sensu lato, Ni is concentrated at a grade of 1–10 wt% (and more), whereas Co may be up to 0.2 wt% (Freyssinet et al. 2005).

The Ni concentration generally reaches a maximum at the base of the profile and ultramafins high in the whole saprolite horizon, but with great variability (Dublet et al. 2012). Considering a mass loss of c. 70% in saprolite (Freyssinet et al. 2005), the theoretically computed residual enrichment alone would result in 0.6–1 wt% Ni (Pelletier 1996b; Brand and Butt 2001). Other factors are therefore necessary to explain the much higher grade commonly observed (Bailly et al. 2014), often referred to as absolute enrichment.

These factors are mainly lithology and structures, which, in turn, control the underground fluid circulation. One particular control is serpentinization. The degree of serpentinization of the protolith is correlated with Ni enrichment (Orloff 1968; Golightly 1979, 1981; Pelletier 1983, 1996a, 2003). The fractional network of the ultramafic protolith is another important factor in mineralization because this is the only way for meteoritic water to circulate. The development of fractures in New Caledonia peridotite is commonly associated with serpentinization and results from a polyphase tectonic evolution that extends over c. 100 myr. It included Late Cretaceous accretion and cooling of the South Loyalty Basin oceanic lithosphere (Maurizot et al. 2020c, Chapter 4, this Memoir), subduction initiated in the Early Eocene, Late Eocene obduction (cf. Maurizot et al. 2020a, Chapter 5, this Memoir) and Neogene post-obduction tectonic events (cf. Sevin et al. 2020, Chapter 7, this Memoir). Some earlier structures were reactivated in each stage. Ni ore can potentially develop as long as the internal drainage is maintained through the fracture network. Most Ni deposits are known to be fault-controlled and faulting was an early guide for miners to follow high-grade garnieritic vein mineralizations (Trescases 1973, 1985; Troly et al. 1978).

When weathering is sufficient, a complete and differentiated profile develops, showing, from base to top (Fig. 10.9d): saprock (20% of the weathered rock); saprolite, in which the inherited bedrock texture is still recognizable, but mass loss is important; laterite sensu stricto, in which all the textures have been erased; and ferricrete on top. Hydroplastic deformation and compaction figures are usual as a result of the change in volume and gravity collapse within
the soft parts of the profile. Spheroidal, incompletely weathered blocks or boulders with the weathering increasing outwards are common in the saprock. The thickness of the saprock varies from 0 to 80 m and it may be the thickest (and most Ni-rich) layer. The thickness of the fine saprolite layer may reach 50 m, which seems to be a maximum. The topmost ferricrete, 0–10 m thick, corresponds to the zone of seasonal oscillation of the subsurface water table, where alternating saturated and unsaturated conditions precipitate Fe oxy-hydroxides. The weathering front may locally drop very deeply (>100 m) due to preferential water circulation in narrow fault gouges.
The detailed mineralogy of the Ni-bearing phases in laterite deposits is beyond the scope of this chapter (for a review, see Brindley and Maksimovic 1974; Brindley 1978; Golightly 1981, 2010; Brand et al. 1998; Elias 2002; Freyssinet et al. 2005; Berger et al. 2011; Butt and Cluzel 2013; Bailly et al. 2014; Fritsch et al. 2014; Cathelineau et al. 2015; Cathelineau et al. 2016). Only significant features and the related references regarding New Caledonian deposits will be presented here.

Many mineral phases incorporate Ni and Co (Fig. 10.9a). Ni may substitute for Fe, Mg, Al or Mn. In fresh peridotite, Ni is mainly incorporated in silicates (mainly olivine) and in serpentine in the phyllosilicates of the serpentine group. In saprock, Ni is predominantly carried by phyllosilicates and subordinately by oxides such as goethite. This trend is reversed in saprolite, where goethite is the main carrier, with some residual phyllosilicates still detected. In the transition zone, Mn oxides may incorporate an important part of the Ni, which decreases upwards.

Serpentinites, mainly lizardite, have an Ni grade similar to that of olivine (Pelletier 2003) and play an important part in the overall Ni mineralization. Early-formed serpentine can be secondarily enriched in Ni up to 3-6 wt% Ni by Mg-Ni substitution in octahedral sites (Besset and Coudray 1978; Pelletier 1983; Dublet et al. 2012) or Ni adsorption (Ammou-Chokroum 1972; Trescases 1975). Early serpentine resulting from the hydration of peridotite is distinguished from the later Ni-bearing neoformed serpentines resulting from weathering that are a component of garnierite (Golightly 1979; Pelletier 1996a). The weathered early serpentine greatly contributes to the Ni grade and, in some places, is the main Ni-bearing phase. The hydrous Mg silicate ore exploited today contains less garnierite than secondarily Ni-enriched serpentine. The degree of serpentinization of the parent rock is therefore an important factor in mineralization and is more important than degree of weathering (Orloff 1968; Pelletier 1996b).

Garnierite is a descriptive term for poorly crystallized Ni-Mg silicates. It is not actually a mineral species, but a mixture of three minerals (serpentinite, talc and smectite), which all vary in composition between magnesian and nickeliferous end-members (Caillère 1936; Kato 1961; Brindley and Pham 1973; Brindley and Maksimovic 1974; Brindley 1978; Pelletier 2003). White-coloured, Mg-rich, Ni-poor garnierite is usually referred to as deweylite (Bish and Brindley 1978).

Garnierite generally forms when early serpentine and Fe oxy-hydroxide are saturated in Ni. Garnierite precipitates in the lower part of the profiles as coatings, boxworks and vein infills, following shears, joints and grain boundaries. Typical high-grade hydrous Mg silicate ore is garnierite-bearing. The filling of open fractures always follows the same order, starting with colloform banded garnierite, followed by recrystallized milky quartz, locally coarse grained around voids, and ending with brown–orange coloured silica (Bailly et al. 2014; Fritsch et al. 2014, 2016). The chemistry and mineralogy of a wide range of New Caledonian garnierites have been extensively investigated (Satsuma 1969; Troy et al. 1978; Ogura et al. 1979; Pelletier 1983; Manca and Calas 1985; Wells et al. 2009; Cathelineau et al. 2016). Nepouite, a Ni-rich neoformed serpentine and a component of garnierite (from Népoui, a mining village at the foothill of Kopéto Massif), may contain as much as 50 wt% Ni (Brindley and Pham 1973; Brindley and Wan 1975).

Above the saprock, at the base of the saprolite, the so-called transition zone contains a number of dark Mn- and Co-rich concretions that include the phyllomanganate family asbolane, lithiophorite and birnesite (Llorca 1993; Fritsch et al. 2014). This assemblage is an important (and underestimated) Ni-bearing phase and the major carrier of Co. The amount of Ni associated with Mn oxides may be up to 30 wt% (Bailly et al. 2014).

Higher in the profile, Ni is mainly hosted by Fe oxy-hydroxides (predominantly goethite). The Ni content in goethite decreases from the bottom to the top of the saprolite, which means that goethite is the essential carrier of Ni in this part of the profile. The Ni in goethite may account for 75% of the total Ni in fine saprolite, whereas asbolane and lithiophorite may account for 25%. The substitution of Fe by Ni in goethite is not easy considering the small radius and charge. The Ni content is correlated with goethite crystallinity and anti-correlated with the proportion of hematite (Trescases 1973; Schellmann 1978; Schwertmann and Latham 1986; Dublet et al. 2012; Fritsch et al. 2014). Ni is expelled from goethite and its content decreases upwards as a consequence of repeated Fe dissolution-recrystallization cycles in the fluctuation zone of the water table (Dublet et al. 2015).

A specific assemblage of mineral phases is reported in several places (e.g. Tiébaghi, Plaine des Lacs and Goro), which includes siderite, smectites and sulfides. These commonly occur in the vicinity of sinkholes or lakes. This assemblage, indicative of a reducing environment, is unexpected in such an oxidizing context. In the Tiébaghi deposit, a specific horizon, 0–3 m thick, develops in some places between the saprock and saprolite (Deraisme et al. 2014). This horizon is nontronite- and smectite-rich, with an Al2O3 content of c. 10 wt% and c. 1.5 wt% Ni. Disseminated sulfides (euhedral pyrite, pentlandite and millerite) are locally present (Bailly et al. 2014). Siderite is also associated and may contain 1 wt% Ni (Dublet et al. 2014). Siderite has been found in association with rhodocrosite in the Ni-rich fine saprolite from the swampy area of Plaine des Lacs (Podwojewski and Boudon 1996) and the Goro deposit (Chen et al. 2004). The anomalous AI content could originate from weathering of the common Early Eocene felsic dykes (Cluzel et al. 2006) or, in the case of Tiébaghi, from plagioclase herzolite. The reducing environment could result from the accumulation of organic matter and from bioactivity at the bottom of ancient lakes (Dublet et al. 2014).

**Typology and examples of mined deposits.** The different Ni-Co deposits of New Caledonia may be classified in several ways. Among the three types of ores known at a global scale, the hydrous Mg silicate and oxide types are the most represented in this country. This classification is, however,
based on mineralogy and it must be taken into account that several mineralogical types may be present in one single deposit (Marsh and Anderson 2011; Villanova-de-Benavent et al. 2014).

Taking into account ore-refining processes and some economic (and historical) aspects, another classification would distinguish the following two types of ore.

- An historical legacy of mines with individual resources <50 Mt ore at a grade >2 wt% Ni, with dominant hydrous Mg silicate ore and subordinate oxide ore. Such mines are spread over the island and represent most of the Eramet-SLN and small local company extraction centres.
- Post-2000, large projects, with resources >150 Mt ore in a single site, of either hydrous Mg silicate- (Koniambo) or oxide-type (Goro), associated with a specific plant devoted to a particular ore.

However, the vocabulary adopted by New Caledonian miners for describing the various ore bodies was commonly influenced by geomorphology and gave rise to terms such as ‘basin deposits’, ‘plateau deposits’ or ‘slope deposits’ (Genna et al. 2005a, b). Some typical examples of these deposits are described here.

**Goro basin setting deposit.** The Goro Ni deposit lies in one of the many flat-bottomed basins and plateaus in the south of the Massif du Sud (Fig. 10.11). These basins represent large weathering cells, decreasing in altitude towards the south and SW. Several other basins are present in this region, with potentially large Ni deposits and at different stages of investigation. The basins, which are surrounded by crest lines, have a typical flat morphology with low relief, a continuous ferricrete cover studded with sinkholes, lakes and wetlands, and are more or less dissected by a few rivers. The flow of groundwater is independent of water on the surface.

The deposit was identified after the Second World War and first explored by drilling from 1968 to 1971. Its specific HPAL process, based on that of Moa Bay in Cuba (the world’s first HPAL plant) was developed in a pilot plant as early as 1969. However, it was only by the 1990s that the economic,
technological and political conditions allowed the launch of the project in its present industrial scale.

The average thickness of the weathering profile is c. 55 m and may reach 90 m in places. An irregular saprock horizon with a hydrous Mg silicate mineralogy, but low Ni content (1.8 wt% Ni) is always present (Wells et al. 2009). The bulk of the deposit is formed by a thick cover of saprolite, c. 25 m thick on average. The oxide-type ore has a grade of 1.3 wt% Ni and 0.11 wt% Co. The stripping ratio is 0.6:1 before removal of the >0.6 mm saprolitic fraction (Golder 2010).

Although a certain structure is outlined on the ferricrete surface by elongated and aligned sinkholes, there is no conspicuous orientation of the alternating depressions and rises of the peridotite bedrock. Semi-variograms do not display preferential spatial orientations of the Ni or Co grades (Bailly et al. 2014). Instead, an egg-box pattern with variable x, y and z dimensions prevails. The saprock with garnierite is thicker in the depressions; however, the thicknesses of the saprock and saprolite are not correlated. Instead, thick laterite seems to develop at the periphery and on the slopes of the deeper saprock zones (Lajoine and Colleau 1978). This distribution is also observed in other types of deposit (Lajoine and Colleau 1976) and means that the development of the hydrous Mg silicate-type ore is favoured by free drainage at the bottom of depressions connected to deep karstic conduits, whereas the oxide-type ore prevails on their flanks in a less drained environment (Fig. 10.12). At the base of the fine saprolite, Ni and Co are highly variable and are correlated with high Mg and Si contents. This has been tentatively explained by the dissolution of former garnierite veins during the downwards progression of weathering (Bailly et al. 2014).

The indicated and measured resources are estimated as 350 Mt of ore from 1.4 to 1.6 wt% Ni is exported. Oxide ore, when present, is stockpiled. The stripping ratio is c. 10:1. A particular ore with specific mineralogical and chemical signatures (the presence of nontronite, carbonate and sulfides) and an Ni content of 1.5 wt% is worked in some parts of the deposit (Deraisme et al. 2014). In some ways, this clay-rich horizon resembles the smectitic or clay silicate Ni ore type.

Camp des Sapins slope setting deposit. Camp des Sapins is a secondary district of the historical Thio mining centre of SLN. It is located on the northern part of the Massif du Sud in a very mountainous and dissected area dominated by Ningua Peak at 1350 m, while the elevation of the main Thio valley is <100 m (Fig. 10.14). Several small mines operated there from 1911 to 2001, with the maximum production during the 1970s boom period. Most of the mines are located at an altitude between 600 and 800 m on slopes between 15 and 40°. They are typically small, 0.1–0.5 km², and each of them has produced between 0.1 and 2 Mt of a fairly rich hydrous Mg silicate ore. The cumulative production is c. 10 Mt ore at 2.8–3 wt% Ni for a cumulative Ni metal content of 250 000 t (compilation of annual reports of the Service des Mines, Government of New Caledonia).

The hillslopes of the Ningua Massif show typical landslide morphologies, with concave upslope areas crowned by scarps, which are often nested. The first-order structures can occupy an entire slope, 2 km wide and 500 m high (Fig. 10.14a). Smaller order structures have a hectometre size. The smallest and lowest structures are dissected and inverted by erosion, with smoothed convex-shaped ridges separated by deeply eroded valleys.

Individual mines are located on ridges. The deposits are exploited by a horizontal bench mining technique. The ore is mainly in saprock and saprolite. There is no ferricrete and the overburden is reduced. Many deposits display a specific rotational landslide-like internal structure, limited at the base by concave upwards faults (Fig. 10.14b). The fault breccia and gouge at the bottom of these lenses are made of weathered products, such as silica (quartz, chalcedony, opal, chrysoprase and prase opal), garnierite and daweyleite with prominent downdip slickensides, indicating movement of gravitational origin. The collapse directions, as indicated by striations and the general morphology, generally conform to the present slopes. The basal faults are often associated with hydraulic breccia and crack seals, indicating fluid-assisted fracturing. The collapsed lens bodies are formed of heavily fractured and deeply weathered peridotite, which are the main hydrous Mg–Ni silicate-rich ore resource. The basal faults commonly overlie fresh non-mineralized peridotite, which acted as a barrier and channelized the mineralized fluids. Such gravitational structures have been described by several researchers (Legueré 1976; Genna et al. 2005b; Cluzel and Vigier 2008; Myagkiy et al. 2015; Issopi et al. 2018), although the invoked driving mechanism differs. Circulating fluids may have greatly reduced the shear strength and favoured slope failure between lithologies of contrasting rheology – namely, the unweathered fresh rock and the low cohesion and highly weathered and mineralized saprock and saprolite.

Fig. 10.12. A schematic section of a typical Goro deposit showing the position of different types of ore.
Most of the gravitational structures are partly controlled by primary fractures in the bedrock. The upslope scarps are aligned along the main bedrock faults (Fig. 10.14c) and Ni-rich veins are guided by pre-existing fractures in the protolith.

Proposed model. Globally, the large-scale morphogenesis of ultramafic rocks under tropical weathering conditions primarily controls Ni concentrations. Many researchers (Trescases 1975; Golightly 1981; Elias 2002; Freyssinet et al. 2005; Lewis et al. 2006) have reported that oxide-dominant ore-bearing deposits are formed where the topographic gradient is low and hydrous Mg silicate-dominant ore-bearing deposits are formed where the topographic gradient is important.

The two end-member deposit types corresponding to two distinct geomorphological contexts are well known in New Caledonia. Oxide-dominant ore-bearing deposits are located in low-altitude basins where the internal drainage is weak, the water table is high, leaching and precipitation are limited, and Ni enrichment is mainly residual in fine saprolite. This setting is exemplified in the south of the Massif du Sud by the Goro and surrounding basins. Hydrous Mg silicate-dominant ore-bearing deposits are located in plateaus or mountainous elevated areas where the internal drainage is free, the water table is low, leaching and precipitation are optimal, and Ni enrichment is mainly absolute and located in the deeper saprock and coarse saprolite. This setting is exemplified by the many perched mines of the west coast peridotite klippen (e.g. Tiébaghi, Koniambo and Kopéto) and the east coast massifs (e.g. Thio and Camp des Sapins). However, a much more complex scheme is needed to account for the mixed-type deposits. A general model for New Caledonian deposits is proposed here.

During the long post-obduction evolution of the island (cf. Sevin et al. 2020, Chapter 7, this Memoir), uplift and eustatic variations in sea-level have developed stepped erosion and weathering surfaces over the Peridotite Nappe (Wirthmann 1965; Avias 1969, 1978; Trescases 1975; Latham 1985; Chevillotte et al. 2004, 2005; Lagabrielle et al. 2005; Chardon and Chevillotte 2006; Sevin et al. 2014). The Miocene post-obduction sedimentary rocks of the Népoui Group attest that positive epeirogenic pulses occurred as early as the Miocene (Sevin et al. 2014; Mau- rizot et al. 2016). The main regolith surfaces on a
longitudinal cross-section along the island delineate an evenly distributed bulge-shaped envelope, offset by a few transversal normal faults (Fig. 10.15). The maximum elevation of this envelope is in the centre of the island, while both ends plunge below sea-level. The main regolith envelope, the associated stepped surfaces and the Ni deposits are all eroded to varying degrees and the original basin topography has been inverted to plateaus, or dissected in the more mountainous regions (Trescases 1973, 1975).

The development of a large lateritic cover containing a substantive Ni deposit requires stable geological conditions and there must be a certain equilibrium between the rate of chemical weathering (deepening of the weathering front) and the rate of uplift to maintain efficient drainage conditions, to redistribute elements (or differentiate the weathering profile) and, last but not least, to grow and retain Ni stocks (Fig. 10.16). Where the rate of uplift is much higher than the rate of weathering, mechanical erosion will destroy any deposit. Where subsidence prevails, the internal drainage is impeded and the Ni concentrations will stop increasing and/or will be buried under sediments. A considerable variety of functional paths between these two extreme situations are possible for the weathering system. The overall typology \( T \) of New Caledonian Ni deposits can be expressed as a function of altitude, \( T = f(z) \), and results in the main settings long known by miners: basin, plateau and slope settings.

The basin-type deposits mainly host oxide-type ores and are located in the south of Grande Terre, where large weathered surfaces are preserved and represent important future resources of Ni and Co for New Caledonia. The geological controls are loose. The stripping ratios are low as a result of the low cut-off grade. Some of these deposits are concealed beneath terrestrial sediments, such as the Fluvio-lacustrine Formation (Folcher et al. 2014, 2015), or drowned below sea-level at both ends of the island (e.g. between the southern tip of the Massif du Sud and the Ile des Pins), where they will probably remain untouchable.

The plateau deposits are topographically inverted former basins (Trescases 1973, 1985). As a result of their large size and continuity, plateau deposits are a favoured exploration target. They are more or less dissected by erosion, so that two sub-types can be distinguished. The first sub-type is continuous, where the topmost resistant ferricrete is continuous (e.g. the Tiébaghi perched plateau), the ferricrete armors and effectively protects the softer underlying horizons from erosion and therefore dissection. The ferricrete also maintains the position and activity of the water table. In these deposits, oxide or hydrous Mg silicate ores coexist and are both currently mined. Fracture control is important. The stripping ratio is significant and groundwater management is an issue. The second sub-type is dissected. On the more dissected plateaus – for example, the Koniombo (Le Carlier de Veslud et al. 2015; Myagkii et al. 2015; Quesnel 2015) or Kopéto deposits –
most of the upper part of the weathering profile has been eroded, although some complete profiles may survive locally. This situation is optimal for creating hydrous Mg silicate ore, with a consequently reduced overburden and stripping ratio. However, the latter can increase dramatically in situations where a large amount of saprock ore requires the removal of a significant fraction of fresh rock cores.

The fracture network plays an important part in these plateau deposits, especially at the mine scale. Several orders of fractures are present and the deposits are controlled by the intersection of two or more orders, resulting in complex patterns such as horst and graben structures, high-angle cross-cutting furrows and ridges or egg-box structures. The deposits are aligned along first-order structures and individual concentrations are located at the intersection with lower-order fractures. The extraction sites in dissected plateaus are distributed in several quarries as more or less elongated pits, hills or slopes (Fig. 10.17).

Slope deposits in the highly dissected mountainous domains have been actively mined since the early times of Ni exploitation in New Caledonia. They are spread out into numerous small deposits on ridges and flanks. Landslide morphologies are common in this specific setting and on most plateau edges (Cluzel and Vigier 2008; Genna et al. 2005a, b; Iseppi et al. 2018). The deposits in these gravitational structures are primarily controlled by extensional faulting and gravitational collapse. They are sharply limited at the base by a concave-upwards fault underlining a heavily fractured and highly weathered lens. Channelling, containment, trapping of the metal-bearing solutions and feedback between fracturing and weathering in this lens is optimal for producing high-grade Ni absolute concentrations hosted mainly in saprock and coarse saprolite. Although the geometry of the deposit is mostly lens-shaped, the internal structure and therefore the Ni grade distribution might be highly chaotic. The overburden is low and so is the stripping ratio, however, the latter can

Fig. 10.15. Simplified geological map of Grande Terre showing the main ultramafic units of the Peridotite Nappe and the associated Ni-bearing regolith surfaces. The projected longitudinal section A–B shows the overall bulge shape of the palaeo-surfaces (modified after Sevin et al. 2012).
increase with the proportion of saprock, similar to plateau deposits. Some deposits are hosted by typical kilometre-sized collapse structures.

**Future of Ni exploration and production in New Caledonia.** Since 2007, Ni laterite has overtaken Ni sulfide in terms of global production and laterite-derived Ni production will continue to increase significantly in the future (Dalvi et al. 2004; Mudd 2010; Mudd and Jowitt 2014). In New Caledonia, low-grade oxide-type deposits will probably represent an increasing part of the production at the expense of the exceptionally rich hydrous Mg silicate-type deposits.

On a regional scale, the architecture and genesis of the New Caledonia Ni deposits are more or less understood. However, at the mine and mineral scales, the extreme variability of Ni...
grade in all ore types remains an issue. In individual mines, Ni
semi-variogram ranges are commonly c. 10 m. As a conse-
quence, the mesh size of exploration or pre-exploitation drill-
ing grids is of the same extent and this results in expensive
exploration programmes. Progress has to be made to better
understand and constraint this variability, specifically at the
metre to 10 m scale. In situ analysis of the Ni content of ore
by portable X-ray fluorescence spectrometry (Quiniou and
Laperche 2014) or reflectance spectroscopy on mine bench
walls (Yang et al. 2013) could greatly improve our under-
standing of the spatial controls on Ni grade.

Other likely future improvements relate to Ni ore processing.
Historically, electrometallurgy has been the dominant
process and this has gradually improved with time. Hydromet-
allurgy, operated since the 1960s, although still with some
unresolved problems in 2014, will probably become the dom-
inant process (Cescutti 2012). At present, other technologies
are under development, such as the Direct Ni process (the
DNi hydrometallurgical leaching process, Direct Nickel
2010), intended to process material from the entire weathering
profile. Techniques such as biohydrometallurgy or bioleaching
may be able to extract more elements, such as Sc and Cr, in addition to Ni, with the help of specific bacteria (Clarke et al. 2006; Du Plessis et al. 2011; Hallberg et al. 2011).

Cobalt

Like Ni, Co is enriched in the weathering profile of peridotites
from c. 150 ppm in the protolith to locally ten times more
in the laterites (Trescases 1975; Troly et al. 1978; Llorca
1982). However, even though weathering is the most common
enrichment process for the two elements, Co and Ni behave
differently.

The Co concentration in hydrous Mg silicate-type ores is
low (c. 0.07 wt%), although it commonly reaches 0.1 wt%
in oxide-type ores (e.g. the Goro deposit). The Co concentra-
tion usually reaches a maximum (0.3 wt%, but locally >1 wt%)
in a transition horizon above saprock and then decreases
upwards. The Co and correlative Mn enrichment in the transi-
tion horizon can be explained by the leaching of Mn and
Co from the near-surface part of the profile (Traoré et al.
2008a, b).

Co was first mined in New Caledonia in 1876. Until 1906,
theses deposits supplied almost all the world’s Co needs from a
number of small deposits spread over the island, most of them
unrelated to the Ni mines (Mudd et al. 2013). At that time, the
Co ore was hand-mined in many adits and pits cut into the sap-
rolite, with specific concretions being picked up, washed and
then concentrated manually at a grade of c. 5 wt%. This kind
of production ceased in 1927, although, by then, about
100 000 t of Co ore had been exported.

Two further unsuccessful episodes of intensive Co pros-
ppecting and some low-level production occurred in 1950 and
1978 as a result of the favourable economic conditions. An
industrial washing unit for Co enrichment was built at
Moné by Eramet-SLN in 1958. The fine saprolite Co-rich
ore at 0.2 wt% Co was concentrated up to 2–3 wt% Co, then
processed in the Doniambo pyrometallurgic plant to produce
a material grading up to 15 wt% Co and 39 wt% Ni (Arène

Fig. 10.17. Some additional examples of Ni deposits (same scales throughout). Dissected plateau settings of (a) Thio and (b) Kopéto. Slope settings controlled by the large gravitational structures of (c) Vulcain mine and (d) the Tchingou Massif.
et al. 1980). Today, Co is a by-product of Ni mining, specifically of the lateritic oxide-type deposits (e.g. at Goro). It is processed separately during the final phases of hydrometallurgical extraction.

Co-bearing minerals are bluish black to grey cryptocrystalline to microcrystalline aggregates (colloform or fibrous) forming intimate intergrowths with Mn–Fe oxides and other poorly crystallized minerals. They appear as spots and coatings along joint surfaces, onion peel weathering structures, as pseudomorphs after silicates (serpentinite veinlets, olivine and talc) and as concretions, mostly rhizoconcretions, in which the vegetal cell structure may be preserved. The observation of encrusted roots shows that the Co deposition probably occurred at a surficial level in the water table fluctuation zone. Live plants with encrusted roots show that Co deposition is still occurring and can be very rapid (Llorca 1993).

Lithiophorite and cryptomelane were identified in New Caledonia in the early 1970s (Perseil 1972). It was later shown that the Co-bearing phases are composed, in various proportions, of several minerals with different Co contents (Llorca 1982, 1986, 1987, 1988, 1991, 1993; Manceau et al. 1987). Co oxy-hydroxides such as heterogenite, phyllomanganates such as asbolan and lithiophorite, and mixtures referred to as asbolan–lithiophorite intermediates are the main Co carriers. Asbolan apparently shows a continuous range of composition between the pure Co and pure Ni end-members. Lithiophorite, the most aluminous mineral, is found mainly in weathering products of dunite, harzburgite or lherzolite. Mn-bearing minerals (e.g. cryptomelane, ramsdellite and todorokite wads) contain only trace amounts of Co.

It has been shown (Llorca 1993) that the Mn–Co oxide mineral paragenesis generally follows the sequence heterogenite, Ni-rich asbolan, Co-rich asbolan, Al rich asbolan–lithiophorite and lithiophorite from saprock (c. pH 8) to laterite sensu stricto (c. pH 6). The precipitation of Co at the base of the saprolite, in the transition zone where the pH is higher, is more effective because the solubility product of Co hydroxide is lower than that of Mn hydroxide (Traoré et al. 2008a, b), thus explaining the higher enrichment factor of Co.

The assessment of the actual resources for by-product metals is difficult (Mudd et al. 2013). About 1500 t CoCl2 is produced by the Eramet refinery from the ferronickel matte produced by the Eramet-SLN Doniambo pyrometallurgical plant (Eramet 2009). The expected annual capacity of the Goro hydrometallurgical plant is 4300–5000 t Co (Golder 2005). The expected annual capacity of the Rivière des Pirogues PGE prospect (Fig. 10.18) is 1100 t Co as carbonate. The resource and reserve are indicated in Table 10.1. Although Co will continue to be exploited as a by-product of Ni, its critical (Roberts and Gunn 2014) and strategic (Wilburn 2012) economic character, new favourable market conditions and improvements in recovery might make it more important in the future.

Chromium

Cr spinel and chromite are disseminated in primary peridotite at concentrations between 0.5 and 1 wt% Cr2O3. Although some studies show that chromite is partly soluble in tropical environments (Phan and Routhier 1964; Traoré et al. 2008a, b), this mineral remains almost unweathered in the laterite profile, where it is thus residually concentrated. These supergene concentrations in laterite have been quarried since the early times of chromite exploitation (1880s), often leading to the discovery of an underlying primary deposit that is much more difficult to mine (e.g. at Tiebaghi; Tessarolo 2013). Residual chromite is a resource that can be extracted and concentrated at low cost by simple processes, notably washing.

However, residual chromite grains are commonly enriched in Fe and coated by Fe oxy-hydroxides, which lowers the Cr to Fe ratio (Traoré et al. 2008b). A special process to improve this ratio is then necessary.

The Alice Louise prospect in the Massif du Sud (Augé and Maurizot 2002) is a good example of a residual deposit in which the volume of the chromite-bearing laterite has been estimated between 5 and 27 Mm3, with a recovery of 100–200 kg m−3. It contains a total of 1100–3200 kg of chromite at a grade of 44 wt% Cr2O3. The economic value of lateritic chromite deposits can be significantly increased by the association of the PGEs with the chromite.

Platinum group elements

The first attempts to evaluate the PGE content of laterite in the south of the Massif du Sud were undertaken in the late 1970s (Ahmad et al. 1977; Ahmad and Morris 1978). Locally strong enrichment in Pt (up to 190 ppb) and Pd (up to 80 ppb) over a barren substratum were reported in random laterite profiles. Subsequent sampling of a variety of weathering profiles throughout the ultramafic units of New Caledonia has shown that the PGEs can be concentrated in laterite, independent of the bedrock lithology (dunite, harzburgite or lherzolite) – for example, the Pt content is commonly >40 ppb, with a maximum value of 150 ppb in weathering profiles, compared with 10 ppb in the underlying fresh peridotite (Augé 1991; Augé and Maurizot 1992; Augé and Legendre 1994, Augé et al. 1995a, b; Traoré et al. 2005). Heavy mineral concentrates obtained by washing the laterite may reach >10 ppm Pt. The PGMs are included in chromite grains in the primary bedrock mineralization, but may be free minerals in the laterite. The PGE and Cr contents, which are correlated in the protolith, are decoupled in the
laterite, indicating the mobility of the PGEs in relation with weathering. PGE-bearing grains extracted from the laterite show complex textures (e.g. dissolution shapes, concentric external concretions, internal banding and fibrous-like shapes). They are rounded, oxidized, acquire a significant porosity and display an apparent volume change, as indicated by many cracks. Some grains also show evidence of Pt migration along crystal cracks. Dissolved PGE minerals recrystallize as new phases in laterite, in particular as Pt–Fe alloys (mainly isoferrroplatinum, Pt3Fe, which accounts for about 60% of the PGMs) and Pt–Fe oxides as Pt–Fe (Cu–Pd) and Rh–Ir–Pt–Fe oxides (Augé and Legendre 1994; Augé and Maurizot 1995; Augé et al. 1995a, b). Some PGE minerals (e.g. oxides found in chromitites) are formed by the oxidation of a PGE alloy precursor, whereas others (e.g. grains with concentration textures) consist of free particles in the laterite and therefore result from the direct crystallization of PGE oxides in the laterite. The minor, but systematic, concentrations of S measured in Pt–Fe oxides suggests that some of them may derive from sulfides (Traoré et al. 2008a).

The Pt : Pd ratio increases from the base to the top of the profile and suggests a higher mobility and a preferential release by weathering of Pd compared with Pt (Traoré et al. 2008a). However, there are many exceptions and in most cases the Pt : Pd distribution is erratic.

From an economic viewpoint, the possible opencast extraction of the Rivière des Pirogues resource is attractive, although the satisfactory industrial-scale metallurgical separation of Pt and Pd from Cr has yet to be developed.

Iron

Extensive surfaces of ferricrete, on top of the laterite profiles, represent an easy method of extracting the Fe resource that has been exploited in the past. For example, Fe was mined by opencast methods in the south of the Massif du Sud in the late 1960s. The so-called ‘mine des japonnais’ near Goro was active from 1938 to 1941. Originally a Japanese industrial project, it was seized and closed by the French Government at the beginning of the Pacific War and never reopened. The production was 415 000 t of Fe ore (Paris 1981; Valet 2014). From 1955 to the late 1960s, 3 176 000 t of Fe ore was extracted in the Prony basin by offscraping a surface of 2.6 km² of ferricrete. The Fe ore grade (55–58 wt% Fe total oxide, with 2–5 wt% Cr2O3 and 0.2–0.3 wt% NiO) was exported to Australia, where it was used in steel metallurgy as a blend with other Fe ores (Valet 2014).

The ferricrete theoretically represent a huge potential resource of Fe ore, readily accessible and easy to mine, particularly in the south of the Massif du Sud. However, the high Cr and Ni content makes it unsuitable for the modern Fe smelting industry. The ferricrete is now considered as an overburden by mining companies and is not recovered. However, it is a good material for base course layers and rip-rap. The environmental impact of its exploitation, which exposes the underlying soft laterite to erosion, is a major issue.

Scandium

Sc, a transition metal commonly associated with the rare earth elements, is naturally dispersed and does not constitute any ore deposits by itself. Globally, Sc is recovered as a by-product from a variety of deposits. The global annual production and consumption of Sc are of a few tonnes per year, however, with its increasing use in modern technologies it has been classified as a critical element by the European Commission (Anonymous 2014) and therefore there might be future exploitation of Sc in New Caledonia.

Sc is a moderately compatible element in magmatic liquids during mantle melting. It is widely dispersed in mafic as well as ultramafic rocks. Like Zr and Al, Sc is a relatively immobile element and is therefore concentrated residually in weathering profiles. The reported Sc contents in global laterite prospects are from 50 to several hundred ppm (Wang et al. 2011; USGS 2014b). Laterites developed on ultramafic protoliths have been identified in several countries as potential targets for Sc deposits associated with Ni and Co (Jaireth et al. 2014). Examples are in Australia, the Philippines and Indonesia. The Australian prospects are located on Alaskan-style layered mafic complexes (Solomon and Groves 1994), whereas the Philippines and Indonesia prospects are ophiolitic and are comparable with those in New Caledonia. Sc is generally found in primary mineral phases such as clinopyroxene, amphibole or biotite. Clinopyroxene may hold 14–64 ppm Sc (Eggins et al. 1998). Clinopyroxene-bearing lithologies (e.g. lherzolite, wehlrite and gabbro cumulates from the mantle–crust transition zone or felsic and amphibolitic dyke-rich areas) would therefore be a favourable primary substrate for exploration in the overlying laterite cover.

Significant Sc contents are reported in several weathering profiles on the Peridotite Nappe. Contents of 55–122 ppm Sc have been early reported in the Goro area (Ahmad et al. 1977; Ahmad and Morris 1978). There are Sc contents up to 50–75 ppm in the Koniambo Ni deposit, with a maximum of 96 ppm in Mn oxides, 70 ppm in goethites, 40 ppm in garnierite and 25 ppm in pyroxenes (Amalric 2002; Audet 2009). Other occurrences are reported in Monéon (26–92 ppm) and Goro (8–74 ppm, with peak values of 200 ppm), although selective extraction did not recover Sc (Bailly et al. 2014). Interestingly, in these localities, Sc is located in the fine saprolite and correlated with Fe, where it is probably carried by goethite or Mn oxides. However, Sc can also be fixed in clay minerals derived from the weathering of plagioclase-bearing lithologies, such as plagioclase lherzolite or gabbros. Which mineral(s) carry Sc is important for processing Sc-bearing ores because its extraction from clay is more difficult than from Fe oxides. In the latter context, Sc has been successfully leached by the HPAL process, with >94% recovery, as a by-product of Ni and Co (Koryakov and Medvedev 1994).

Alluvial and littoral deposits

Chromite

Chromite grains are considerably enriched in the sand fraction of most rivers that have part or all of their catchment in peridotite. Chromites grains are residually concentrated in the weathering profile. The heavy minerals are then easily separated from the soft laterite by physical erosion and form conspicuous and ubiquitous trails and lenses in the hydrosystem onshore, along the shore and in the near-offshore in the lagoon. The fine-grained chromite fraction is important in the estuaries of the main rivers and stream–wave interactions lead to the accumulation of large amounts of washed and clean chromite sands. The chromite sand is accumulated along beaches by coastal currents and winnowing. The resulting placers and sand beach chromite deposits represent a valuable resource, which is easy to extract, process and concentrate by conventional operations. As such, they have been long coveted (Fig. 10.19a). Chromite grains in such contexts may have varying shapes, from euhedral fresh crystals to rounded and weathered grains, most commonly enriched and coated by Fe oxides or included in pisoliths. The chrome to Fe ratio of the latter are thus low and a special process might be
necessary to improve it. Magnetite and PGMs are accessory minerals that improve the value of these deposits.

A short-lived exploitation of chromite sands was operated in 1952 at the Franco mine over an area of 100 km² west of Poya. The deposit occurs in a deltaic to coastal environment, fed by the Népoui River, the catchment bedrock of which includes the Kopéto ultramafic massif. The chromite-rich sand was a layer c. 1 m thick at 5 wt% Cr₂O₃, grading to 20 wt% near the shore. The washing plant produced c. 5000 t of Cr₂O₃ at a grade of 50 wt% with a Cr : Fe ratio of 2.4. In the early 1980s, Unocal reported unverified resources in the Rivière des Pirogues, N’Go and Ouiné river estuaries, surveyed by drilling, at an average grade of 3–4 wt% Cr₂O₃ over thicknesses >10 m (UNOCAL 1986).

There have been several attempts to assess the chromite resources of the Fluvio-lacustrine Formation, which fills great depressions in the south of the Massif du Sud (Folcher et al. 2013). The sedimentary rock infill, of maximum thickness of c. 60 m, comprises lateritic clay, silt, sand and a few conglomerates. It mainly represents reworking of the different weathering products of the ultramafic protolith, composed largely of chromite-rich dunite. The sands are locally strongly enriched in chromite. The formation was prospected by pits in the 1970s (Kieft 1963; Lajoinie and Colleau 1976; Colleau 1977; Maurizot 1990, 1992a). Unfortunately, residual chromite in the laterite cover was included with that from alluvial placers in grade calculations and an average recovery of 100–150 kg m⁻³ chromite, of all types was obtained for a grade of 45–50 wt% Cr₂O₃ by the usual washing and gravitational processes. For the Fluvio-lacustrine Formation only, the Cr content is c. 30 wt% Cr₂O₃ with a Cr : Fe ratio of 1.3 or lower and a recovery <50%. For the in situ laterite, the residual chromite content is c. 46 wt% Cr₂O₃ with a higher Cr : Fe ratio of 2.6 and a recovery >50% (Maurizot 1990, 1992a).

A small and unusual deposit of chromite sand is known in the Baie de Saint Vincent, at the Pointe Guillois (Avias 1965), in the Late Pleistocene–Holocene eolianites accumulated during low sea-level of the last glacial period (cf. Sevin et al. 2020, Chapter 7, this Memoir). The environmental impact on the lagoon and reef of such exploitation makes future exploitation very unlikely.

**Platinum group minerals**

The value of chromite-rich sands as placers or sand beach deposits might be greatly enhanced by the occurrences of PGMs, either as inclusions in chromite minerals (if...
Mineral resources of the ultramafic rocks

recovered) or as free grains. Several such occurrences are known and some of them have been prospected. Chromite sands resulting from the weathering and erosion of the mantle–crust transition zone (i.e. from the south of the Massif du Sud) are probably enriched in Pt and Pd PGMs. Streams, lakes, estuaries and beaches in this area are potentially good targets (Fig. 10.19a, b).

A large stream drains into the Ni estuary from the harzburgite of the eastern coast of the Massif du Sud. Here, high PGE contents and a large diversity of PGMs were detected in samples of chromiferous beach sand (Chiron et al. 1986; Augé 1993). The chromite crystals are larger than usually observed in such rocks and most of the PGMs are in the 50–100 µm fraction. Systematic sampling of the Ni estuary beach showed that the mineralization is discontinuous and restricted to the chromite-rich horizons. Two bulk samples of sediment contained 400 and 780 ppb Pt and very low concentrations (<40 ppb) of the other PGEs (Maurizot and Augé 1995). Chromite sands from old chromite mining areas have been prospected by auger sampling (Augé and Maurizot 2002). The average Pt content is remarkably constant along the section varying from 80 to 170 ppb Pt, but low (about 30 ppb Pt). The PGM potential of the chromite-rich sediments of the Fluvio-lacustrine Formation has been tested (Augé 1996; Augé and Maurizot 2002). Chromite sands from old chromite prospecting pits have an average grade of 60 ppb Pt. Only one pit provided an interesting Pt enrichment, with relatively low (6.2 for Ru sulfide) and the complex angular shapes observed favour a short transport distance. No exploration of this remote watershed has been attempted and, as yet, there is no indication of the potential primary source that has provided the PGMs. There is no equivalent report of this type of alluvial deposit, marked by a great variety of PGMs and dominated by Pt minerals.

The Baie Tranquille flat of Ile Ouen is located in a deep large bay, exposed windward to the dominant trade winds from the SE. Its watershed drains the PGE-enriched upper mantle–lower crust transitional zone. This configuration has been suspected to be favourable for trapping alluvial PGMs. The flat has been prospected by auger sampling (Augé and Maurizot 2002). The average Pt content is remarkably constant, but low (about 30 ppb Pt).

The PGM potential of the chromite-rich sediments of the Fluvio-lacustrine Formation has been tested (Augé 1996; Augé and Maurizot 2002). Chromite sands from old chromite prospecting pits have an average grade of 60 ppb Pt. Only one pit provided an interesting Pt enrichment, with relatively constant contents along the section varying from 80 to 250 ppb and an average of 165 ppb Pt for ten samples. The Pd values are low.

The fluvial sediments of the flat situated downstream of the Rivière des Pirogues PGE primary deposits (Fig. 10.19) have been drilled and core sampled (Augé 1996). The sediments, 5–9 m thick, have an average content of 130–170 ppb Pt, with a maximum at 700 ppb, in the bulk material. The average content of the chromite-rich layers is 200 ppb Pt.

In general, the PGE content, mainly Pt, of all types of chromite-rich sands remains low, even where the primary source is in the favourable upper mantle–lower crust transitional zone and in the vicinity of known occurrences of PGEs. These low concentrations could, however, probably be enhanced by any typical refining process.

Conclusions

The Peridotite Nappe, accreted onto the Norfolk Ridge at the end of Eocene and covering one-third of the area of New Caledonia, is by far the leading provider of country’s economically useful mineral resources. Chromite is present in the ultramafic protolith, in the laterite profiles, and in rivers, estuaries, beaches and probably also the offshore sediments. Hypogene chromitite pods have been actively prospected from the end of the nineteenth century and mined up to the 1990s. The small Tébaghi Massif provided most of the production. Its ilherzolitic composition and the occurrence of the largest chromitite pods in the country are probably related. No primary chromite deposit in New Caledonia is currently economically competitive.

The main occurrences of PGEs are not related to the typical chromitite pods, but are concentrated in the disseminated chromite of the transitional mantle–crust zone, where they constitute small deposits that might have some economic interest in the future. Chromite and the PGEs are concentrated in the weathering profiles and in the alluvial to littoral domains. The PGE content of such chromite deposits should always be taken into account when assessing their resource.

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