Mineral resources and prospectivity of non-ultramafic rocks of New Caledonia

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Abstract :

The mineral resources of the non-ultramafic rocks of New Caledonia and its Exclusive Economic Zone can be classified according to their host rocks. The metallic mineral resources are essentially associated with volcanic and magmatic activity. Non-economic volcanogenic massive sulfide deposits with Cu and Au are located in the Late Carboniferous Koh Ophiolite and in the Late Cretaceous Poya Terrane. Base metals, Au and Ag of the sedimentary–exhalative type are present in the metamorphic Diahot-Panié Metamorphic Complex, associated with syn-rift volcanism. An Au–Sb metallogenic province is associated with the post-obduction Late Oligocene granitoids and co-genetic hydrothermal silica–carbonate (listwanite) zones in the Peridotite Nappe; Au is disseminated in the granites and Sb occurs as lodes in the silica–carbonate. Among the non-metallic mineral resources, barite, gypsum, magnesite, phosphate, clays, dimension stones, limestone for use as cement and as a neutralizer, and aggregates are all present. Gemstones such as jade and chrysoprase are only used locally. Late Cretaceous coal, which was briefly exploited in the past, is now considered to be a source rock for an offshore potential oil and gas system. Petroleum prospectivity is currently focused on the Fairway Basin. Several low-enthalpy thermo-mineral springs with a weak geothermal energy potential are known on Grande Terre.

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The mineral resources of New Caledonia are strongly controlled by its specific geology, which is dominated by mafic-ultramafic ophiolitic and arc-related lithologies. This chapter is devoted to the mineral resources, metallic or not, unrelated to ultramafic terrane. Mineral resources hosted by the Peridotite Nappe are the object of chapter 10, this memoir. Those resources which are present in both ultramafic and non-ultralafic terranes (e.g. thermo-mineral springs or gemstones) are grouped for convenience in this chapter. The metallic resources unrelated to ultramafic terrane are essentially associated with volcanic and magmatic activity.

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 nickel. In the early 1980s, due to the drop in nickel price, the French Government launched a systematic mineral exploration programme aiming at diversification of the mining industry. This "Mineral Resources Survey" programme was conducted by the French Bureau de Recherches Géologiques et Minières (BRGM) between 1980 and 1990. It comprised greenfield surveys (stream sediments and alluvial concentrates) and brownfield exploration (soil geochemistry, geophysics, drillings), and involved all metals except nickel. It led to the development of a few prospects, especially gold, which were subsequently held by junior companies. Although this programme ultimately did not lead to the discovery of new economic-size deposits, it resulted in acquisition of priceless knowledge and scientific advances.

In the 1990s the ZoNéCo programme (Zone Economique de Nouvelle-Calédonie), was launched to explore the Economic Exclusive Zone (EEZ) of New Caledonia in order to assess its offshore resources (Ducrocq *et al.* 2012; Grandperrin *et al.* 1997). Part of this programme, still active in 2016, is specifically devoted to hydrocarbon potential linked to thick sedimentary piles, deposited on shore and offshore.

In this paper, the terminology, such as reserve and resource, is used in compliance with recommendations and guidelines of instances such as the Committee for Mineral Reserves International Reporting Standards (CRIRSCO). A mineral occurrence is of geological interest but not necessarily of economic interest. A prospect is a mineral deposit on which some preliminary prospection or mining works have been done. A mineral deposit is a generic term applying to a concentration of material, economic or not. A mineral resource is a concentration of material economically and technically feasible or not. A mineral reserve is the economically mineable part of the mineral resource.

Information on many of these resources (e.g. coal, base metal, chromium, gold, gypsum, etc.) is only documented in unpublished reports in the French language, most of them available in the archive of the New Caledonia government administration in charge of mines: Direction de l'Industrie, des Mines et de l'Energie de Nouvelle-Calédonie (DIMENC). Irrespective of abundance or importance, all 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.

Geological setting

The mineral resources addressed in this chapter, are presented by genetic type rather than by chronological order. For easier reading, the main outlines of the geology of the archipelago are presented first (Fig. 1), with emphasis on those units having mineral resources or potential.

The geological evolution of Grande Terre, the main island of New Caledonia, may be divided into four phases (Cluzel *et al.* 2012).

Fig. 1 a) Geological map of New Caledonia. b) EEZ of New Caledonia and position of some remote islands. c) Legend showing (in red) main metallic mineral resources (including ultramafic related, cf. chapter 10, this memoir), hydrocarbons, phosphate, and their associated terrane. VMS: Volcanogenic Massive Sulphide; Sedex: Sedimentary Exhalative; BM: Base Metals.

The Late Carboniferous to Early Cretaceous period, is marked by west-dipping subduction along the eastern Gondwanaland margin. At that time, proto-New Caledonia was located in a fore-arc region in which volcanic-arc detritus accumulated whilst oceanic and terrigenous material accreted from the east. The amalgamation of the three resulting terranes constitute the 'basement' of New Caledonia (cf. chapter 3, this memoir, and Maurizot *et al.* in press). Téremba Terrane is composed of deep-sea Permian to Mesozoic arc-derived volcanic rocks and greywackes. The Koh-Central Terrane includes at its base an ophiolite (Koh Ophiolite) of Late Carboniferous to Early Permian (Aitchison *et al.* 1995a; Meffre *et al.* 1996) age overlain by a thick sequence of greywacke (Central Range volcanoclastic rocks) of Permian to Late Jurassic age. The Boghen Terrane is a High Pressure - Low Temperature (HP-LT) metamorphic subduction complex composed of schists, broken formations, and mafic/ultramafic mélange, derived from mixed terrigenous and volcanic sources, Early Jurassic to Early Cretaceous in age.

After this prolonged period of convergence, the eastern Gondwana margin underwent a rapid change to extensional tectonics, evidenced by a major angular unconformity between the older 'basement' rocks and the younger sedimentary 'cover' (cf. chapter 4, this memoir). During this Late Cretaceous–Palaeocene period, continental break up, and marginal rifting isolated New Caledonia in an intra-oceanic setting. After a Late Cretaceous period of shallow water terrigenous sedimentation, including coal deposits ('Formation à charbon') associated with volcanic activity, pelagic sediments ('Mamelons Rouges' beds then Black Cherts) accumulated during post-rift thermal subsidence (Aitchison *et al.* 1995b).

At the Paleocene-Eocene boundary, a new NE-dipping subduction appeared to the east of New Caledonia (Cluzel *et al.* 2001) that led to the formation of the 'subduction-obduction complex' (cf. chapter 5, this memoir). In this new convergence zone, the northern tip of the Norfolk Ridge is gradually subducted during the Eocene, and metamorphosed to HP-LT schists and gneisses. The exhumed parts of this subduction complex form the Diahot and Pouébo terranes (Cluzel *et al.* 1994). At the front of the convergence zone, a typical thick turbidite succession, the Eocene Flysch, accumulated in a flexural foreland basin propagating from NE to SW (Maurizot 2014). The subduction blocked when the Norfolk Ridge entered the convergence zone at the end of Eocene. This collisional and obduction stage resulted in the SW-ward in-sequence stacking of allochthonous terranes over the Norfolk Ridge: successively the margin of the Norfolk Ridge (Montagnes Blanches Nappe, Maurizot 2011), the oceanic crust of the South Loyalty Basin (SLB, Poya Terrane), and finally the Peridotite Nappe, deep mantle sequence of the Loyalty Basin (Cluzel *et al.* 2001).

The 'post-obduction formations' (cf. chapter 7, this memoir) are represented by a variety of geological units. Two calc-alkaline granites (Saint Louis and Koum) of Late Oligocene age (Cluzel *et al.* 2005) are intruded both in the peridotite nappe and its substrate. They are associated with extensive hydrothermalised zones of silicification and carbonatisation in the peridotite. Finally, during Neogene, New Caledonia definitively emerged; In the terrestrial domain, this period mainly corresponds to prominent regolith development under tropical climate, and intramontane deposits, the Fluvio-Lacustrine Formation, (Folcher *et al.* 2015) on the Peridotite Nappe. It led to the development of supergene nickel ores as well (cf. chapter 10, this memoir). In the marine domain, mixed carbonate and siliciclastic platform deposits (Maurizot *et al.* 2016) lead offshore to deep basinal deposits.

The geology of the Loyalty Ridge is poorly known (cf. chapter 6, this memoir). The ridge is formed by seamounts of volcanic origin, covered by thick Miocene to Recent carbonate platform.

Mathew and Hunter Islands (cf. chapter 2, this memoir), the easternmost islands of the New Caledonian archipelago, are isolated volcanoes located on the southern tip of the Vanuatu island arc, marking one of the active convergent boundaries between the Pacific and Australian plates.

The Chesterfield Islands (cf. chapter 2, this memoir), the westernmost islands of New Caledonia, are atolls built on intra-oceanic volcanoes that belong to the NS Lord Howe hotspot trail, roughly parallel to the eastern coast of Australia.

Metallic mineral resources

Submarine volcanism

A number of base metal, gold, and silver of the generic volcanogenic massive sulphide (VMS) type (Large 1992), together with some manganese occurrences, are known in various volcano-sedimentary terranes of the basement, cover, and ophiolitic allochthons. The deposits typically result from leaching by volcanic-related hydrothermal convective circulation of seawater-derived fluids in the country rocks, then precipitation, at or immediately below the seafloor by venting of hot metal-bearing solutions. These deposits typically combines a lower root where fluids are entrapped in a stockwork of veinlets crosscutting the host rock (stringer zone), and an upper, more or less stratiform body where fluids are deposited in the open sea, and are interfingering with the surrounding sediments, if present.

Ophiolitic rocks

Subordinate exhalative hydrothermal deposits with copper, gold, of modest sizes are hosted by both the sedimentary rocks and the mafic volcanic rocks of the two main ophiolitic crustal terranes of New Caledonia i.e. the Paleozoic Koh Ophiolite and Mesozoic Poya terranes (Fig. 2).

Fig. 2 Locations of the main VMS and manganese deposits in the Koh Ophiolite and Poya Terrane.

Koh Terrane

The Koh-Central Terrane (Meffre 1995) includes the Late Carboniferous to Early Permian Koh Ophiolite (Aitchison *et al.* 1998), and its Central Range volcanoclastic sedimentary cover (Aitchison *et al.* 1995). The Koh ophiolite is composed of dismembered fragments of oceanic crust comprising gabbro cumulate, dolerite, dyke complex, pillow basalt, breccias, flows, pyroclastic deposits, and radiolarian chert. Boninite are known in the Koh massif (Cameron 1989; Meffre 1995; Meffre *et al.* 1996).

In the Koh massif, the New Monta prospect consists of several occurrences of copper and gold, extending discontinuously over 2 km along strike. Disused workings, as old as 1875, consist of several trenches, addits and pits of c. 10 m in size. More recently, a Mineral Resources Survey programme (BRGM 1987a, BRGM 1981) consisted of a stream sediment survey, soil and rock geochemistry, geophysics, drillings, and detailed geological mapping. Sulphides at New Monta occur as small quartz veins, silicified brecciated zones, or disseminated crystals in boninites, tholeiites, pelagic cherts and tuffs of the top of the Koh Ophiolite. No mineralization is reported from the underlying layered gabbros. The Cu content is generally below 1 %, although it may reach 6 % very locally, in local gossan. The average Au content is below 1 ppm in fresh rock but may occasionally reach 5 to 35 ppm in gossan. Ag is also present in oxidised zones with a grade of 1 to 2 ppm. Sulphides comprise chalcopyrite with minute inclusions of palladium telluride, galena, and electrum, pyrite (commonly nickeliferous), and

pyrrhotite. Sulphides are associated with oxides, as chromite, chromium-spinel, ilmenite, and rutile (BRGM 1981). The presence of Ni, Cr and Pd in the mineralization is consistent with boninite host rock (cf. chapter 3, this memoir).

The Queyras prospect (BRGM 1982) was discovered in 1896 in the Pocquereux – Kuah ophiolitic massif. A few pits, adits, and a quarry were excavated in fractured basalt overlain by gossan extending over a maximum of 100 m. Sulphides appear in a stockwork of quartz veins and in basalts heavily altered to chlorite and epidote. The paragenesis is made up of pyrite and magnetite with inclusions of chalcopyrite, pyrrhotite, galena, and pearceite (a Ag, Cu, As sulphide) derived from hydrothermal deposits of low to medium temperature. Grades in the gossan are as high as 70 ppm Au and 20 ppm Ag. A few tons of ore were extracted and exported.

Both the New Monta and Queyras deposits have been formed in an oceanic seafloor setting. They are dominantly vein deposits corresponding to hydrothermal pipe and stockwork zone in basalts, and subordinately hosted in exhalative sedimentary rocks.

Poya Terrane

The Poya Terrane (Aitchison *et al.* 1995b; Cluzel *et al.* 1995b; Cluzel *et al.* 2001) corresponds to a pile of stacked, scraped-off slices of oceanic crust, overthrust onto the New Caledonia autochthonous basement (Norfolk Ridge) below the Peridotite Nappe. Its age is Late Cretaceous (Campanian) to Paleocene. This crustal ophiolitic unit is composed of pillow lava basalts, dolerites, fine grained gabbros, and subordinate sediment intercalations. It is devoid of any mantle or cumulate sequences. E-MORB tholeiites are preponderant over IAT, BABB and depleted N-MORB tholeiites. Minor, variously colored, sedimentary intercalations are red, green, white or black ferro-manganiferous jaspers, radiolarian cherts, and argillites which represent thin draping of abyssal sediments deposited over the oceanic floor.

The basaltic protolith is often cross cut by hydrothermal veins whose proportion may sometimes be higher than the host rock. Such host rocks are uniformly and pervasively affected by a hydrothermal sub-seafloor low grade metamorphism related to hot rock and sea water interaction. The whole is severely disrupted and cross cut by numerous shear planes and tension gashes. Interbedded sedimentary inliers are generally fault-bounded and dip steeply (Cluzel *et al.* 2001).

Poya Terrane VMS deposits are linked to sedimentary inliers and are copper and gold dominant (Bache 1981; Bache & Wilhelm 1980; BRGM 1980). No stringer zone with quartz-sulphide veins has been identified so far, owing to the bad quality of outcrops, severe tectonic disruption, and small size of the deposits. Barite together with silica as quartz-chalcedony is a gangue mineral in several deposits. The size of the deposits are modest; c. 10 to 50 m long, highly contorted, folded and faulted, with an average thickness of c. 1 m, exceptionally and locally 10 m (Honfleur mine). Deposits were all primarily identified by their gossan in which Au content was commonly enriched to over 100 ppm, and exceptionally 1000 ppm. In the non-oxidized zone, Cu content is c. 5-15 %, Au 1-10 ppm and Ag 0-50 ppm. Sulphides are chalcopyrite and pyrite (euhedral or colloform) with common spheroidal or framboidal textures. Electrum and native gold grains (up to 200 µm in Edison mine) are frequent. Accessory minerals are sphalerite, galena, tetrahedrite, and Ni bearing species like gersdorffite and melonite (a nickel telluride, Bache 1981).

In the Azema deposit, clusters of unjointed worm tubes made up of pyrite with an annealed structure in the quartz-barite gangue of the massive sulphide ore have been reported (Oudin *et al.* 1985), 1 to 2 mm in length and 300 μm in diameter, representing the remains of a former seafloor hydrothermal vent with its associated living community.

The Pouébo Terrane is a metamorphic high pressure – low temperature metamorphosed equivalent of the Poya Terrane, underplated at depth c. 70 km, with which it shares both geochemical composition (Cluzel *et al.* 2001) and age of formation (Spandler *et al.* 2004a; Spandler *et al.* 2004b; Spandler *et al.* 2005). It corresponds to a chaotic mixture of boulders within a metasedimentary or serpentinite matrix (Maurizot *et al.* 1989) metamorphosed to eclogite facies then retrograded through blueschist to greenschist facies. Several small occurrences of Cu and Au sulphide deposits in this unit are metamorphosed equivalent of the Poya Terrane VMS deposits.

VMS deposits of the Poya and Pouébo Terrane are of the Cyprus type (Constantinou 1980), deposited in oceanic seafloor settings, far from any clastic source. Individual extracted tonnages are of the order of a few hundred tons, to be compared to the 1.6 Mt average tonnages of the Cyprus type (Mosier *et al.* 2009).

Small manganese deposits in the Poya Terrane have been sporadically quarried from 1918 to 1922 then from 1949 to 1953 (Arnould 1954, 1956). The overall extracted tonnage is 61 000 t for this two periods with a Mn content of c. 50 % and 10 to 20 % Si. Deposits are clearly associated with abyssal sedimentary intercalations of argillite and chert, and display the same structural complexity. The ore is mainly composed of braunite also with psilomelane and pyrolusite. Barite is an accompanying mineral (Arnould 1954). Individual lenses are c. 10 to 100 m in length and c. 1 to 10 m in width, for a maximum tonnage of 10 000 t. These volcanogenic sedimentary deposits have no clear spatial relations with the Cu-Au bearing VMS.

In some places (e.g. Nétéa) primary manganese deposits are enriched and concentrated in weathering profiles, as Mn-rich red clays including residual boulders of Mn bearing cherts.

Cretaceous volcanism

Base metal and gold deposits of the Diahot Basin, in the north of New Caledonia (Fig. 3), were discovered early after the colonization, in the 1870s, soon after the Australian (1850s) and New Zealand (1860s) gold rushes. Despite their modest size, they led to several waves of interest, speculation, hope, and disappointment. The Fern Hill gold deposit was the first one to be discovered and, because of this, gold was the first metal to be extracted in New Caledonia, before nickel (Black 2004). Other deposits of base metals were discovered and exploited subsequently. Mining works progressively declined until 1895, and by the eve of WWI, most operations had ceased. All following attempts to revive the mining, throughout the 20th century, even with modern exploration tools and appropriate metallogenic models, were unsuccessful. The last reassessment of the Diahot Basin metallogenic potential was made in the 1980s by the Mineral Resource Survey French governmental programme, operated by the BRGM (Aye 1982; Bache 1981; BRGM 1981, 1986c, 1987a; Maurizot 1981). Following this programme, several promoted targets were taken by junior companies but no economic target arose. The geological context and the metallogeny of the deposits were at least scientifically studied.

Base metal and gold deposits of the Diahot Basin are located in the HP-LT metamorphic complex of the north of the island which comprises the Diahot and Pouebo terranes (Clarke *et al.* 1997; Cluzel *et al.* 1995a; Cluzel *et al.* 1995c), subducted during Late Eocene. The deposits are stratiform, hosted in sedimentary rocks and related to the volcanic activity and rocks of the Late Cretaceous Diahot Terrane (Cluzel *et al.* 2012; Maurizot *et al.* 1989). The metamorphic grade is blueschist (lawsonite – glaucophane blueschists) on the true left bank (SW) of the Diahot River and eclogite (omphacite - garnet) on the true right bank (NE). Interestingly, the same Late Cretaceous cover in the Noumea area, with a very similar lithology (Noesmoen 1970), but a slight different geochemistry and unmetamorphosed (Black 1995; Nicholson *et al.* 2011), is sterile in term of metal deposits.

Fig. 3 Diahot Basin geological map and mineral deposits: a) Extent of the Late Cretaceous Diahot Terrane. b) Geological map. c) Cross section.

Economic data

A total of sixty prospects have been identified and explored in the Diahot Basin, but only five deposits, with significant size and tonnage, were mined (Table 1).

Name	Element	Minerals	Production	Reserve	Activity	Grade
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Pilou	Cu, (Pb, Zn)	Chalcopyrite, sphalerite, galena	70 000 t	90 000 t	1884 - 1910	Cu 10 % Zn Pb 5 %
Ao	Cu, (Pb, Zn)	Chalcopyrite, sphalerite, galena	0	30 000 t	1887 - 1900	Cu 15 % Pb 1 % Ag 100 g/t
Mérétrice	Zn, Pb, (Ag)	Sphalerite, galena, chalcopyrite	15 000 t	35 000 t	1884 - 1930	Zn 30 % Pb 15 % Cu 5 % Ag 200 g/t
Ballade	Cu	Chalcopyrite	60 000 t	100 000 t 5 % Cu	1872 - 1884	Cu 20 %
Fern Hill	Au, (Zn, Pb)	Native gold, (sphalerite, galena)	213 kg	?	1870 - 1890	Au 1 – 100 g/t

Table 1 Summary of metallogenic and economic data of the main mines of the Diahot Basin. Locations on Fig. 3. Mined tonnages or reserves do not exceed 100 000 t.

Regional protolith

The Late Cretaceous sedimentary rocks of the Diahot Terrane correspond to a rifted margin megasequence, deposited on the northern thinned margin of the Norfolk Ridge, with syn-rift terrigenous deposits towards the base and post-rift finer-grained deposits towards the top. A few fossil occurrences and lithological comparisons with unmetamorphosed areas to the south enable to reconstruct a general stratigraphic column, despite the complex and polyphased deformation and metamorphism (Maurizot *et al.* 1989).

To the SW of the Diahot River, the syn-rift terrigenous meta-sandstones, -siltstones, and -argillites, are well exposed although a basal conglomerate, if any, is not known. This unit extends toward the SE over considerable surfaces in the remote area, covered by tropical forest of the Mont Panié Massif (Fig. 3a). It grades upward into a series of very fine grained, organic-rich, carbonaceous black argillites, metamorphosed as black phyllitic schists. This black schists are interbedded with volcanic rocks of bimodal composition. Mafic lavas are dolerite or porphyric basalts of transitional tholeiite to alkaline affinities (Cluzel *et al.* 2011; Cluzel *et al.* 1995c; Picard 1995). An intrusive origin as sills has been proposed (Briggs 1977) because of the lack of co-eval mafic pyroclastic sediments and sharp contact with the enclosing schists, but is difficult to ascertain in such a metamorphic context. Acidic lavas are rhyolite and rhyodacites with phenocrysts of K-feldspars or plagioclase. Co-eval acidic tuff sequences, with volcanic quartz clasts, interbedded in the schists are common. Acidic lavas are commonly considerably altered with development of epigenetic quartz, phyllosilicates and oxidised sulphides. The rocks usually show strong iron staining and leaching. Cu and Pb content is frequently of the order of 100 ppm.

This unit passes transitionally upward to siliceous black schists, typical of the Mamelons Rouges beds (Tissot & Noesmoen 1958), in which fossiliferous nodules yielded Late Cretaceous inoceramids in several localities. To the SW, in the unmetamorphosed area of Koumac, the Mamelons Rouges beds are assigned to the Coniacian–Early Campanian interval (Maurizot 2011). They grade upward into Late-Campanian-Maastrichtian cherts, then to Paleocene micrite.

The Late Cretaceous black schist and metachert sequences reflect a period of considerable reduction in terrigenous input and an anoxic bathyal environment, related to a post-rift thermal relaxation (Aitchison *et al.* 1995a).

Description of deposits

Deposits show a remarkable degree of bedding control from regional to macroscopic scales (Fig. 3 and fig. 4). Stratiform mineralisation likely took place during a short episode of the Late Cretaceous, in carbonaceous black argillites, and in association with volcanic activity. Sizes of orebodies are c. 100 x 50 m, for a maximum thickness of 1 m. They are complexly folded. Massive layers of sulphides have a high grade in base metal, higher than 10 %. Exceptional grades of c. 35 % are noteworthy at the Pb-Zn deposit of Mérétrice.

Most of the deposits show varying degrees of compositional banding of sulphides and, in places, the sulphide ores show relict sedimentary textures (Briggs 1975, 1977; Briggs *et al.* 1978). In the Pb-Zn ores at Meretrice and Fern Hill the compositional layering consists of millimetric beds of galena, pyrite-chalcopryrite-rich layers, in a matrix of compact sphalerite. Small scale cross-bedding and slumping structures are visible in the layered ore. Pyrite framboids and atoll structures of sedimentary or diagenetic origin are also common. There are complex concentric structures with several envelopes of galena and pyrite in the ore at Meretrice. In Balade, Pilou, and Ao copper mines, the compositional layering in the compact massive chalcopryrite consists of millimetric to decimetric discontinuous trails of pyrite, sphalerite, and galena (BRGM 1987a).

Other lithologies are specifically associated with the deposits. Calc-silicate lenses and layers (Pilou, Mérétrice) are formed of massive heterogeneous breccias of quartz, calcite, and dolomite, with disseminated sulphides. Calcite is euhedral and seems to have crystallised directly in seawater before being cemented by quartz which fills voids. Quartz veins with euhedral ferrocapholite are present in this facies which is frequently found in continuity either with rhyolite or with massive sulphide layers, e.g. at Pilou and Ao mines (Briggs 1978). Spotted black schists are also common. They show millimetre diameter, ellipsoid flattened porphyroblasts, with pressure shadows, filled with fibrous radiating aggregates of quartz, sericite, pyrophyllite, carpholite or chlorite. Fe-Mg-carpholite in the blue schist zone is replaced by a Fe-chloritoid in the higher grade eclogite zone, e.g. in the Ballade mine (Black *et al.* 1993).

Layers (after bedding) of sericite, chlorite, talc, or any combination of these phases, centimetre to decimetre in thickness, are also common in the vicinity of the deposits. Iron rich quartz chlorite-schists at Fern Hill and Ballade comprise hectometre to kilometre along-strike bodies hosting disseminated sulphide mineralization. All these lithologies are considered to result from sedimentation of hydrothermal exhalations, either proximal (calc-silicate) or distal (schists) from vents (Aye 1982).

Fig. 4 Geological maps and cross sections of a) Pilou mine; b) Mérétrix mine.

In the Fern Hill gold mine, two types of mineralization occur. Type 1 corresponds to disseminated pyrite, arsenopyrite and other base metal sulphides in quartz schist or quartz-chlorite schist with barite, and discrete lenses of meta-acidic tuffs. Native gold is present as infra-millimetric grains in the pyritic ore. The "discovery trench" was opened on the oxidized part of this primary type deposit where contents from 100 to 1 000 g/t Au were reported. Type 2 corresponds to a massive rich layered Zn-Pb ore (similar to the one at Mérétrix) with sphalerite and galena. This part of the orebody was reached later by deep underground works and subsequent drilling, and does not outcrop. Gold content of 380 g/t corresponding to millimetric native gold particles in this ore were reported. A low base metal and gold background with localized high grade gold concentrations seems to be the rule. So far, controlling factors of the erratic gold contents are not known.

At Balade, there are so far no recognized acidic volcanic rocks associated with the ore. Sulphide lenses are intercalated in iron and disseminated sulphide-rich quartz-chlorite-schists that form a distinctive weathered rusty horizon, approximately 80 m thick, which extends over 2 km along strike. In this layer, massive chalcopyrite ore forms localized lenses.

Even though there is a dominant metal in each deposit, each of them contains an amount, even if minor, of the Cu, Pb, Zn, Au, and Ag. The Cu Ballade ore contains minor amount of gold (1 ppm in the gossan and 0.5 ppm in sulphide) and locally up to 200 ppm Ag. Part of the Fern Hill Au deposit is rich in Pb-Zn. The Pb-Zn-Ag Mérétrix deposit contains minor amount of Cu and Au (1 ppm in the gossan). Because of this elemental consistency the deposits of the Diahot Basin can be considered as a single metallogenic province (BRGM 1987a).

All the deposits are characteristically pyritic. Cu is the most abundant element, mainly as chalcopyrite, followed by Zn and Pb in sphalerite–galena layered ore. Sphalerite is the most abundant phase of the Pb-Zn deposits, and contains inclusion of cassiterite. Au is in native form and is most significant at Fern Hill. Much less significant are Ag, As, Sb, Sn, Mo, Bi. Ag occurs in argentiferous galena at Meretrix. Arsenic is locally abundant, occurring in arsenopyrite and tetrahedrite. Laminae, rich in arsenopyrite and tetrahedrite occur at Meretrix where an almost monomineralic tetrahedrite layer is reported (Briggs 1977). Sb and As are in minerals from the tennantite-tetrahedrite series (Pilou), and in enargite. Sn is mineralogically expressed as cassiterite, kesterite, mawsonite and stannoidite. Bi-bearing minerals have been identified in two Cu Pb Bi-sulphosalts at Ao and as phases from the bismuthinite-aikinite series at Ballade. Tellurides as hessite and tetradyte are mentioned at Balade. Ni-Co bearing sulphides like mackinawite and cobaltite are reported in Ballade and Fern Hill (BRGM 1987a; Maurizot 1981; Maurizot *et al.* 1989).

Deposits share the complex and polyphase deformation and metamorphism of their host rocks. The Diahot Terrane rocks have been subducted at depths of c. 50 km (1.7 GPa - 550°C). The protoliths display well developed penetrative foliation and stretching lineation. This lineation is related to the exhumation of the protolith with an almost constant NE-SW trend (Clarke *et al.* 1997; Cluzel *et al.* 1995). Sulphides display a general increase in grain size which parallels that of the silicates in the enclosing host rocks (Briggs 1975; Briggs *et al.* 1978). Most of the deposits are highly folded, stretched, and boudinaged. On the SW bank of the Diahot River the initially stratiform deposits are isoclinally folded and the main mined ore bodies are lenses or in thickened hinges (e.g. Pilou, Meretrix). On the NE bank of the Diahot River, in the high grade metamorphic zone, the mineralization zones are mainly controlled by the stretching lineation as elongated columns (e.g. Fern Hill, Balade). Where deformation has contributed to local thickening of mineralization, it however results in difficulty in laterally tracing the orebodies.

Fig. 5 Original basinal control of the Diahot deposits.

Genetic model

Deposits of the Diahot Basin correspond to the sedimentary-exhalative (SEDEX) stratiform sulphide type (Carne & Cathro 1982; Klau & Large 1980; Large 1980; Large 1992). Some sulphide lenses are clearly in continuity with metavolcanic rocks. The abundance of disseminated sulphides within many acidic meta-tuffs or -flows suggests a close genetic relation with that rock type. The absence of any mineralization associated with the meta-basaltic rocks discount them as source rocks, although their geographic extent is similar to that of the deposits.

Despite severe deformation and recrystallization, the distribution of deposits from SW to NE seems to reflect some original organization and structure in the sedimentary basin (Maurizot et al. 1989) (Fig. 5). The deposits to the SW of the Diahot River (Pilou, Mérétrice, and subsequent minor deposits) in the blueschist zone are associated with a regionally mappable complex of meta-rhyolite, meta-tuffs, and calc-silicate layers which in turn continue into layered orebodies. The deposits are in sharp contact with their blueschist host rocks and form a few solid sulphide-rich layers. The deposits are Cu, Pb, and Zn-rich. To the NE of the Diahot River, in the eclogite zone, acidic volcanic rocks are represented by meta-tuff (Fern Hill) or are lacking (Ballade). Individual high grade deposits are present in an envelope of low grade disseminated ore with a typical hydrothermal mineralogic fingerprint. Dominant metals are Cu and Au.

The above relationships suggest that the Diahot Basin deposits formed in a NW-SE half graben with a border fault close to the SW of the Pilou-Meretrice alignment that controlled acidic volcanic eruptive centres. In this proximal context, deposits are closely related to acidic volcanic centres. To the NE, deposits are likely in a deeper part of the basin, away from volcanic centres. In these distal locations, mineralizing hydrothermal fluids were more diluted. This configuration led to a zonation in term of type and metal deposit.

In the SEDEX model, deposits are usually enclosed in intracratonic or epicratonic extensional fault-bounded rift basins and half grabens developed by extension along continental margins, a context which is consistent with the interpretation of the Diahot Terrane as the northern thinned and rifted

margin of the Norfolk Ridge of Zealandia (Clarke *et al.* 1997; Cluzel *et al.* 2001). The permeable syn-rift terrigenous sedimentary rocks play the role of reservoir leached by hydrothermal circulation systems related to volcanic activity. In the post-rift overlying less-permeable carbonaceous black shales, deposited in an anoxic, reducing, and starved environment, metals are precipitated as sulphides on the seafloor by reaction with the overlying reducing seawater column. If the role of the volcanism as a heat source generating fluid circulation seems clear, the part played by the acidic volcanism, closely associated with sulphides and metals (as compared with the mafic compositions which are barren of any mineralization) remains unclear.

Worldwide, SEDEX deposits are generally restricted to second and third order subbasins (Large 1980; Large 1992), a fact that is consistent with the small extent of the Diahot metallogenic province in the more widespread Late Cretaceous co-eval sedimentary unit of the Diahot Terrane (Fig. 3a). Globally, SEDEX deposits are an important resource for Zn and Pb and account for, respectively, more than 50% and 60% of the world's reserves of these elements (Tikkanen 1986). Economic deposits of this type of deposit have worldwide a median tonnage of 15 Mt. The Diahot Basin deposits, with a maximum inferred reserve of c. 100 000 t for a few mines, represent a very minor and, at present, non-economic resource.

ADIO LIMESTONE

A small manganese deposit is hosted by the basal conglomerate of the PaleoceneADIO Limestone (Maurizot 2013) which unconformably overlies the schists of the Boghen basement terrane (Fig. 2). Manganese minerals occur in elongated and isolated clusters by replacement of the matrix and clasts of the conglomerate, particularly in the coarser facies. Mn impregnation increases towards the base of the conglomerate until it forms a continuous layer where pseudomorphing is complete (Avias & Routhier 1962). 1 220 t of ore have been extracted from a small surface quarry at an average grade of 48 wt % Mn. When compared to the manganese deposits of the Poya Terrane, the SiO₂ content is low (3 %).

This single representative of the manganese sedimentary deposit type (Dill 2010) is not related to any volcanic source. It is likely associated with the weathering of a continental land mass and has been deposited at the base of a transgressing shallow marine limestone.

POST-OBDUCTION MAGMATISM

Two post-obduction km-size granodioritic calc-alkaline plutons intrude the Peridotite Nappe and its autochthonous substrate (Fig. 6), in the Massif du Sud. U-Pb dating of magmatic zircons gave ages of 27.5 Ma for Saint Louis granodiorite, near Noumea, and 24 Ma for the Koum adamellite on the eastern coast, i.e. Late Oligocene (Cluzel *et al.* 2005; Paquette & Cluzel 2007). Both granodiorites are composed of a main ellipsoid pluton and a stock of peripheral comagmatic dykes. Although some dykes of the Saint Louis pluton clearly intrude various rocks of the autochthonous substrate (Late Cretaceous to Eocene sedimentary cover) and display contact metamorphism with it, the bulk of the granodiorite is enclosed in the ultramafic rocks where it is associated with large serpentinised dislocation zones including the basal thrust sole of the Peridotite Nappe.

Within the ultramafic rocks, plutons and related dykes are associated with extensive hydrothermalised zones of silicification and carbonitisation, locally named "silica wall", which actually correspond to "listwanite", a term first coined by Rose (Rose 1837), or its synonym "silica-carbonate" (Buckman & Ashley 2010), a term that prevails in the English-speaking countries. Carbonatization (ferroan-dolomite,

ankerite, magnesite) and silicification (quartz) of the serpentinite host-rock is generated by CO_2 - SiO_2 - H_2O hydrothermal fluid. Relict minerals from the ultramafic host rock such as chromite are diagnostic.

In the Massif du Sud, silica-carbonates (listwanites) form important vein zones, in close association with the granodioritic plutons or away from them, either in the basal serpentinitised thrust sole of the Peridotite Nappe, or in serpentinite slivers in the autochthon. Both granodiorite and listwanite have significant anomalous concentrations of As, Au, Sb, Hg, and W, in contrast with the ultramafic host rock which is almost devoid of these elements. In the area between Thio and Nakety, listwanites have erratic but significant contents of As (500 to 1000 ppm), Sb (35 to 300 ppm), W (20 to 300 ppm), and less frequently in Au (> 100 ppb) (Aye *et al.* 1986; Aye & Jacob 1983; Jacob 1985).

Gold has been actively prospected in the area of the Saint Louis and Koum plutons by the Mineral Resources Survey programme (BRGM 1987b, 1988, 1990a, b, c, d) although no economic target has yet been identified. Antimony, as stibnite lodes, has been mined in the area of Nakety on the east coast at the end of the 19th century. The main characteristics of the different deposits are summarized in table 2.

Fig. 6 Simplified geological map showing the principal features of the As, Au, Sb, Hg, W mineralizations associated with granodioritic post-obduction intrusions and silica-carbonate (listwanite). Small yellow labels: showings; Orange labels: deposits.

Name	Major element(s)	Minor elements	Main minerals	Alteration	Production (t)	Reserve
Nakety	Sb (Au)	As, Hg	Stibnite Arsenopyrite		1 500 t at 25 % Sb	2 500 t at 10 % Sb 500 kg Au at 3 g/t
Koum D1	Au	As, W, Bi, BM	Arsenopyrite	Beresitisation		9 t Au at 0.1 g/t Au
Saint Louis	Au	As, Li, W, Mo, Bi, Te BM, Sb	Arsenopyrite	K, Si		NA

Table 2 Summary of metallogenic and economic data of the main deposits of the As, Au, Sb post-obduction mineralization. BM: base metals (Cu, Pb, Zn).

Koum gold deposit

Koum pluton (Fig. 7b) is intrusive into a disrupted zone of the Peridotite Nappe which runs parallel to the east coast, associated with a large serpentinite area. The regional fracture pattern in the ultramafic host rock is composed of two conjugate sets with dominant dextral NW-SE and subordinate sinistral NE-SW strike-slip faults. Anomalous As and Au contents were discovered in E-W striking dykes (Koum D1) to the east of Grand Koum pluton during the Mineral Resource Survey programme (BRGM 1980).

The Koum D1 dyke is a 2.2 km long structure with a maximum width of 300 m (Fig. 7c). It was actively prospected from 1980 to 1987 by the Mineral Resources Survey programme (BRGM 1987b), then by different junior companies from 1989 to 1998. Methods used were soil geochemistry, alluvial concentrates, groove sampling along trenches, auger sampling, and core drillings. The D1 structure is a complex assemblage of listwanite and granodiorite. Among several facies, porphyritic microgranite with quartz and feldspar phenocrysts and microgranite with sericite are the most common. There is no evidence of any preferred orientation fabric in the granodiorite which usually displays an equigranular texture. To the west, the E-W trend of D1 displays obvious dextral offsets; however the granodiorite in these areas does not show any correlative brittle or ductile deformation, a fact that is indicative of a post-fault intrusion. Silico-carbonates (listwanites) are dominant in the wall of the D1 structure/dyke but may also be found as inclusions within the granodiorite. Granodiorite-silico-carbonate relationships are very complex in detail but the contact is always sharp and clearly intrusive.

Secondary alteration phases are always present in the granodiorite and consist of muscovite, sericite, chlorite, albite, ferroan and magnesian carbonates (ankerite, breunnerite, dolomite), quartz, silica, and sulphides. Sulphides are disseminated within the granite or in quartz veinlets. They are represented by pyrite, arsenopyrite, minerals from the tennantite-tetrahedrite series, chalcopyrite, sphalerite, jamesonite, and pyrrhotite. This assemblage is typical of granite beresitisation (Rose 1837), a low-temperature metasomatic alteration associated with a variety of gold bearing deposits in acidic igneous rocks, and a term commonly used in Russian literature. Silico-carbonate (listwanite) is considered as the result of beresitisation process in ultrabasic rocks (Zharikov *et al.* 2007). The listwanite-granitoid-beresite association is commonly referenced in the Ural goldfields (e.g. Berezovsk goldfield, type locality of listwanite) and in other Russian auriferous districts (Baksheev *et al.* 1999; Laznicka 2006; Likhoidov *et al.* 2007).

Rocks are highly weathered with thick laterite development on ultramafic rocks. Granodiorite is rarely fresh, and usually is transformed to grit or quartz sand down to 40 m depth (BRGM 1987b, c).

Fig. 7 Geological maps of Saint Louis and Koum (same scale) post-obduction granodiorites with associated mineralisations. a) Saint Louis geological maps showing the complex relationship of the granodiorite with both autochthonous substrate and allochthonous Poya Terrane and Peridotite Nappe. b) Koum geological map. c) Detailed map of Koum D1 gold prospect; dashed red rectangle encloses the area with 2 ppm Au average content.

Gold was never recovered in alluvial concentrates and free gold grains are never observed in polished thin sections. Instead, gold is apparently chemically bound within arsenopyrite. In Koum D1 dyke, gold anomalies are located mainly near the many contacts between granodiorite and listwanite either on both edges of the dyke or inside silica-carbonate (listwanite) lenses in the dyke. Au has a high variability from 10 to several 1 000 ppb in listwanite. Up to 14 ppm Au content was found repeatedly in listwanite. Au content of granodiorite is 100 ppb in average, and the 100 ppb Au isopleth corresponds roughly to the granodiorite margins. The 800 ppb Au isopleth coincides with most of the granodiorite-listwanite contacts. On the whole, Au content increases within the granodiorite towards the listwanite wall rock with values often higher than 10 ppm. At a larger scale, Au content increases towards the east where the granite pinches out. In this area, over a length of 500 m, the average content of soil samples is c. 2 ppm Au. In places, decametric long and narrow large metre-scale veins, reach a content of 5 to 10 ppm. A maximum content of 50 ppm Au was locally found in auger sampling. Beside this primary lithologic control, a supergene gold enrichment is marked in many drill cores by a depletion of

the average gold grade with depth. Au is correlated with Sb, As, K, W, Bi, and Pb. Au, As, Sb, and W are present in the listwanite. Au is not detected in the ultramafic host rock (< 3 ppb), whilst As, Sb, and W, are sporadically in significant amount (BRGM 1987b).

Rolling bottle cyanuration tests indicate a possible recovery of 90 to 99 % of the gold. The gold content of the whole Koum D1 structure has been roughly estimated at 9 t of metal for a down dip extent of 100 m and a cut-off grade of 0.1 ppm. The rock being weathered to a depth of 20-40 m, it could be partly extracted in an open pit and processed by heap leaching (BRGM 1987b).

The overall succession of events in the Koum area can be summarized as follow: i) NW-SE dextral transpressive faulting and correlative pull-apart opening of conjugate NE-SW structures in the peridotite. ii) Hydrothermalism of host ultramafic rock as silica-carbonate (listwanite), which are precursor of the granite and are offset by dextral strike slip faults. iii) Passive intruding of the granite in the pre-fractured peridotite and listwanite (which are found as inclusions within granite). iv) Hydrothermalism of the granite and to a lesser extent of the listwanite with sulphide impregnation.

As well as the listwanite-granitoid-beresite model, the Koum D1 deposit may be compared to other intrusion-related gold systems (IRGS; Lang *et al.* 2000), a low-grade, large-tonnage, post-deformational, granite-hosted gold deposit model.

Saint Louis gold deposit

The Saint Louis pluton is a hornblende–biotite granodiorite with numerous subvolcanic dykes and comagmatic enclaves (Cluzel *et al.* 2005; Lemennicier *et al.*, 1998, 1999; Paquette & Cluzel 2007). The main Grosses Gouttes batholith is deeply eroded by the Thy River (Fig. 7a). The smaller Comète intrusion, to the NE, is separated from the Saint Louis intrusion by a major transcurrent dextral fault zone. It corresponds to a more apical subvolcanic part of the pluton, covered with thick colluvium and weathering products, and surrounded by silica-carbonate (listwanite). Listwanite occurrences are controlled by fault zones.

Gold flakes, blebs and small nuggets, extracted by alluvial or eluvial wash on the current site of Comète, were reported at the beginning of European settlement (Glasser 1904). Two occurrences of molybdenite are known, in the Grosses Gouttes batholith, and in a separate dyke intruding the Late Cretaceous sedimentary rocks, 6 km to the SE of the granodiorite. At the southwestern contact of the Saint Louis pluton, Paleocene limestone is locally transformed to garnet and scheelite bearing skarn (Guillon & Trescases 1976).

A regional prospectivity study undertaken by the Mineral Resources Survey programme, using sieved stream-sediments (BRGM 1980) highlighted several geochemical anomalies in As, W and Au (40 to 80 ppb Au) in the Comète watershed. A subsequent exploration campaign included soil geochemistry, alluvial concentrates, trenches, auger sampling, and core drilling (BRGM 1986a, 1987c). The higher Au contents, in soil and rock, are centered on the granitic part of Comète pluton rather than the surrounding listwanite.

Mineralization is hosted exclusively in quartz veined, sulphide bearing, and hydrothermally altered granite, with K-feldspar and phengite pseudomorphs after plagioclase, biotite and hornblende. In the high grade alteration zones, the granite is proto-mylonitized and brecciated. The main hydrothermally altered zones and quartz veins trend in a NS direction. Mineralisation is composed of pyrrhotite, pyrite

and marcasite with epitaxial arsenopyrite (with up to 0.1 % Au content), chalcopyrite with sphalerite exsolutions, minerals from the tenantite-terahedrite series, molybdenite with telluro-bismuthinite inclusions, scheelite, rare native gold, tetradymite, rutile, and leucoxene (BRGM 1986a, 1987c).

Three main anomalies are distinguished inside an area of average 100 ppb Au content, within which, isolated values of 1 ppm Au occur. The largest mineralized zone is 500 m long and 50 m wide. At depth it has been traced down to 30 m by drilling. These zones are characterized by numerous quartz veins in a granitic saprolite. The drilling has crosscut decimetre to metre-size lengths of veined granite with 1 to 10 ppm Au. One rock sample of silicified granite with disseminated sulphides yielded a maximum content of 20 ppm Au. Au content has a high variability. Au, As, Li, K, Si, W, Cu, Zn and Sb are correlated.

As in the case of Koum granodiorite, supergene gold enrichment is shown by depletion of the average gold grade with depth in drill core. The Comète intrusive body, deeply weathered, forms a modern geomorphic basin whose outlet is blocked to the SW by a NW-SE trending listwanite bar. This particular topography favored the colluvial accumulation of residual fragments of quartz veins and gold nuggets upstream in the Comète basin that led to the early discovery of the prospect.

The Saint Louis gold potential is less important than Koum. So, therefore, is its economic interest. The nature of both deposits differ significantly in term of sulphide mineralogy, geochemistry, alteration, gold content, and host rock (Table 2). The Saint Louis gold deposit corresponds to the plutonic porphyry gold deposit model (Sillitoe 2010) a well-known large tonnage, low-grade type of resource, associated with shallow intrusions, with pervasive potassic or phyllic alteration, and the association of Au, Bi, W, and Mo. However, with only 0.5 km², it is far from having the size and metal content of the economic standard porphyry gold deposits which are in the range of 25 to 100 km².

Nakety antimony deposit

The Nakety antimony deposit is the only significant occurrence of this metal recognized to date in New Caledonia. It is of lode type and contains gold as well.

The earliest works of the Nakety antimony mine date back to 1879. The operation itself (several hundred metres of underground works) lasted only three years (1883-1885). This work extracted 1 500 t of ore at a grade of about 25 wt % Sb. Since then and until 1982, when the Mineral Resources Survey programme tried to reassess the deposit (soil geochemistry, geophysics, trenches, and c. 900 m of core drillings, Aye *et al.* 1986; Aye & Jacob 1983; BRGM 1986a; Chiron *et al.* 1986; Jacob 1985), no substantial work, exploration or development, took place.

The deposit is hosted by a c. 100 m thick sliver of Late Cretaceous black shales and cherts from the Montagne Blanche Nappe, heavily sheared inbetween overlying serpentinite slices connected to the basal sole of the Peridotite Nappe, and underlying Mesozoic greywackes of the Central Terrane. Serpentinite is often altered into silica-carbonate (listwanite). The deposit is in the form of a discontinuous, roughly en echelon, vein system, which extends over a length of 1 250 m (Fig. 8). Most of the veins are hosted within the Late Cretaceous shales but some of them crosscut the basal greywackes. Individual stibnite veins extend over c. 100 m in length for a thickness of 0.1 to 3 m, and have been crosscut by drilling down dip to c. 100 m.

Complex brecciation and filling of the dykes indicate a multiphase process under variable tectonic conditions. Two major hydrothermal phases with two different types of quartz veins are reported

(Chiron *et al.* 1986): i) an early network of oxidized gold bearing quartz veins, with very little antimony; ii) a late network of pure white quartz veins, with or without stibnite. Stibnite distribution is discontinuous and irregular, either disseminated or massive. Massive stibnite is generally restricted to the footwall of the dykes, filling voids, in a clearly extensional context. Quartz is the usual gangue mineral, sometimes with barite, but small pockets of stibnite may occur directly in the sedimentary host rock.

The mineral paragenesis is simple and can be summarized in essence as stibnite and arsenopyrite. Gold and antimony mineralization is relatively independent, thus agreeing with the observation of two specific quartz vein generations. The gold content of the ore is from 2 to 5 ppm in average. The highest gold values are associated with high values of arsenic and low values of antimony. The gold is partly related to arsenopyrite whose earlier deposition relative to stibnite is microscopically observed. Gold is never observed macroscopically or in polished section. Accessory or rare mineral phases are pyrite, sphalerite, scheelite, cinnabar, and galena. Reserves for a down dip extent of 100 m are estimated to 2 500 t at 10 % Sb and 500 kg Au at 3 ppm cutoff (BRGM 1986b).

The Nakety Sb-lode can be classified as a structure-bound antimony deposit type (Dill 2010) which is typically shear zone-hosted, in the mesothermal field, in a distal position relative to a heat zone, with a limited mineralogy made up chiefly of stibnite.

Fig. 8 a-b) Geological maps and c) cross sections of the Nakéty antimony deposit.

Other occurrences

A number of small, scattered showings of Au, Sb, W, and Hg are associated with the main silica-carbonate (listwanite) lenses or major regional fault zones in a variety of formations (Fig. 6). Their mineralogy includes arsenopyrite, cinnabar, realgar, and scheelite. Only the significant ones are briefly described below.

To the east of Canala, scheelite, cinnabar, and datolite (CaBSiO_4OH) are associated in small quartz-carbonate veins crosscutting the Boghen Terrane (Glasser 1904).

The mercury deposit of Col des Roussettes has been known since 1893 and has been prospected at different periods (Maurizot 1981). The mineralisation forms irregular coatings and veinlets in fractures and joints of a highly sheared fault zone underlying the Mé Maoya peridotite klippe. The recognisable host rocks include mica schists of the Boghen Terrane and the calcareous Eocene Flysch. The Hg and Au contents are generally low and erratic. Maximum reported contents are of 2.5 wt % Hg and 2 ppm

Au. Mineral carriers are cinnabar and droplets of native mercury. Reserve has been assessed to 400 000 t of ore at 0.5 wt % Hg (Colleau *et al.* 1978). These Hg occurrences corresponds to the California-type cinnabar deposits (Laznicka 2006), connected to a serpentinite fault zone, but hosted in sedimentary rocks, especially those rich in carbon, more prone to entrap it.

Genetic model

Silica-carbonates (listwanites) worldwide, are associated with the emplacement of late-orogenic granitic rocks (Likhoidov *et al.* 2007). They commonly host the As, Au, Sb, W, Hg association (Buisson & Leblanc 1986; Goncharenko 1970; Halls & Zhao 1995; Laznicka 2006). In this association, Hg has a more independent behaviour, being often disconnected from the main crustal scale discontinuities.

In New Caledonia, listwanite and granodiorite are two cogenetic hydrothermal and magmatic expressions of post-obduction events. Emplacement of plutons and surrounding listwanites is controlled by the post-obduction steeply dipping pre-existing fault pattern at the mine scale, and by the contact between allochthonous serpentinitized basal sole of the Peridotite Nappe and autochthonous substrate at a regional scale. Granitoids and listwanites are present only in the Massif du Sud and its east coast extension, never in other ultramafic units located farther north.

Listwanites and intrusives form an original metallogenic provinces involving three deposits with Au and Sb which have had or may have an economic interest. Au is the common element to these three deposits. Au is mainly associated with intrusives while Sb is always related to silica-carbonate (listwanite). Other accompanying and accessory elements are W, Mo, Bi, and base metals. Hg is distal from granitoids and often unrelated with listwanites. Saint Louis granite has a distinct association in Mo, Li, and Te. Both Saint Louis and Koum plutons display the same spatial arrangement with a main roughly elliptic plutons to the west and smaller mineralized satellites and apophyses to the east.

A more detailed analysis allows the differentiation of several types of mineralization and settings related to the obduction event.

The Late Oligocene plutons were first interpreted as a product of the melting of the underlying continental crust (i.e. the Norfolk Ridge, Rodgers 1973, 1976). However an origin in an active margin setting has been more recently proposed (Cluzel *et al.* 2005) on the grounds of isotopic geochemical data. In this model, after the blocking of the Late Eocene subduction zone by the continental Norfolk Ridge, the Saint Louis intrusion (27 Ma) resulted from the onset of a new short lived NE dipping subduction along the SW coast generating active margin magma. In this model, the younger Koum intrusion (24 Ma) resulted from the break-off of the older slab (Sevin *et al.* 2014), leading to the formation of a slab window, asthenosphere upwell, thermal perturbation, and melting of the overriding plate. This two stage intrusion model is consistent with the two types of gold deposits associated with the post-obduction granitoids. The synorogenic porphyry type Saint Louis deposit, is compatible with an intrusion generated in the overriding plate by active subduction. Its modest size accounts for a short lived period of subduction. The rapid exhumation and weathering of the pluton, dated at c. 18 Ma by K/Ar on Mn oxide (Bailly *et al.* 2014), is also consistent with a shallow emplacement that fits the typical porphyry deposit model (commonly in the range of 1-5 km depth, Sillitoe 2010). The younger Koum pluton intruded the Peridotite Nappe in a different and more passive context. There, the associated gold deposit is essentially fault-controlled.

The New Caledonia silica-carbonates (listwanites) are both precursors and distal expressions of the hydrothermal alteration associated with the post-obduction intrusions. Listwanite occurrences may be located quite far from granites (Nakéty Sb deposits is at 45 km from Koum granodiorite) but their majority is either closely associated and in contact with plutons or in the basal thrust contact of the Peridotite Nappe. Some listwanites are sterile (e.g. Dumbéa, Fig. 6) but most have an anomalous geochemical background in As, Au, Sb, W, and Hg.

Uncertain type

An unusual group of small copper deposits is located in the Massif du Sud at Pic Casse Cou (Guillon 1972). It consists of five lenses of 0.5 to 1.2 m in thickness, c. 10 m in length, associated with a serpentinite shear zone. The shear zone crosscuts dunite below the cumulate sequence of Montagne des Sources. The ore is composed of magnetite and chalcopyrite with c. 10 wt % Cu. A few tons were extracted in 1920. This occurrence might be related to the many dykes (Cluzel *et al.* 2006) crosscutting the Peridotite Nappe which are however usually devoid of such copper mineralisation.

Offshore metallic mineral resources

Although there has yet to be any actual economic exploitation, deep sea metallic mineral resources (polymetallic nodules, ferro-manganese crusts, and massive sulphide deposits) have attracted perennial attention around the world and particularly in the SW Pacific area. Some area of the New Caledonia EEZ could be favourable for the formation and preservation of such deep sea resources.

Polymetallic nodules are generally found in deep abyssal plains where sedimentation rates are very low. Such conditions are thought to be present in the D'Entrecasteaux Basin and possibly the North Loyalty and South Fiji basins. However only a few nodules have been dredged in the EEZ of New Caledonia, and they were found not in the abyssal plain but, fortuitously, on seamounts and ridges (D'Entrecasteaux and Loyalty ridges, Laurent 2011).

Ferro-manganese crusts develop at depth below 400 m on hard surfaces sheltered from the pelagic sedimentation (Fouquet & Lacroix 2012). They are generally found on ridges and seamounts where a combination of low sedimentation rates, steep slopes and currents prevent any accumulation of sediments. The seafloor of the EEZ of New Caledonia contains many such rises, ridges and seamounts (Pascal *et al.* 1992; Vanney *et al.* 1992). Centimetre thick ferro-manganese crust have been dredged along the Loyalty Ridge and near to the Récif d'Entrecasteaux (Lafoy *et al.* 1996), with a low content of 0.5 % wt Co (Pichocki & Hoffert 1987). A specific site, offshore NE from Tiga (20°47'S-167°31'E, at 1400-1700m depth) has yielded ferro-manganese crusts with tiny inclusions of gold and silver (Bolton *et al.* 1986).

The uninhabited Matthew and Hunter volcanic islands, and the surrounding New Caledonia EEZ, belong geologically to the southeastern termination of the active New Hebrides subduction zone and volcanic arc (Fig. 9). Detailed bathymetric surveys (Patriat *et al.* 2015) show that back-arc extension of the North Fiji Basin is propagating southwestward into the arc in a rifted area characterized by numerous volcanic centres. Dredged samples show an uncommon diversity of fluids and magmas (Danyushevsky *et al.* 2006), known to be usually associated with massive sulphides deposits.

Fig. 9 Matthew and Hunter islands along with other volcanic structures forming an island arc, at the southeastern termination of the New Hebrides subduction zone. A N-S spreading ridge (thick red line with arrow) is visible in the NE, propagating to the SW into the arc. White line to the east and north: limits of the New Caledonia EEZ; EB: D'Entrecasteaux Basin; LR: Loyalty Ridge; NLB: North Loyalty Basin; NFB: North Fiji Basin.

Non-metallic mineral resources

Fig. 10 Map of non metallic, hydrocarbon, and gemstone mineral resources of onshore New Caledonia.

Magnesite

Magnesite as nodules and cauliflower-shaped concretions, 10 to 50 cm in diameter, is often present in various post-obduction units along the west coast of New Caledonia. Magnesium leached from the ultramafic massifs precipitates as carbonate in many lithologies: Miocene Népoui sedimentary rocks (mainly conglomerates as clasts or in the matrix), serpentinites of the basal sole of the Peridotite Nappe, serpentinite slivers in the Poya Terrane, and magnesium-rich soils (vertisols). Sheared magnesite veins of meteoritic origin, according to oxygen isotopic composition, in the serpentinite sole of the Koniambo ultramafic massif, indicate that weathering was already active during obduction (Quesnel *et al.* 2013).

Magnesite deposits have been quarried and used locally in the nickel industry to change the Mg content of the ore and in the smelting process of Doniambo plant (Nouméa, cf. chapter 9, this memoir) as refractory (Lebret & Maurizot 2007). From 1943 to 1968 the total production was 33 500 t, of which 21 000 t were extracted in the Népoui-Poya area and 12 500 t near Koumac, at an average of 45 wt % Mg with less than 3 wt % Si. From 1955 to 1959, 15 300 t of magnesite were exported to Australia (Broken Hill Proprietary).

From an economic view point, magnesite deposits are presently of low importance as a source for either magnesium or carbonate. Today, a new scientific interest has arisen, to try to better understand naturally occurring carbonation reactions at near surface conditions, and their implications for engineered in situ CO₂-sequestration processes by injection of CO₂ bearing fluid in ultramafic and mafic lithologies (Kelemen & Matter 2008).

Gypsum

In New Caledonia gypsum is known on the south western coast and islands of Baie de Saint Vincent. Inland or in the marshland area, gypsum is always associated with clays. Clays bearing gypsum were at first all interpreted as marine evaporitic deposits (Avias 1953; Gonord 1968; Piroutet 1917; Routhier 1953). Later on, a distinction was made between two different types of occurrences.

In the marshland tidal zone of Mara, near Baie de Téremba (Avias 1952; Baltzer 1965), gypsum occurs at a depth of 10 to 80 cm. Crystals, as 1 to 10 centimetre long sticks or lenses, often twinned, are disseminated inside ferruginous clay. Their origin is still unclear. It could be either evaporitic or related to the weathering of sulphides of the bedrock (greywackes of the Téremba Terrane).

The majority of occurrences are actually located inland (up to 10 km), at altitudes up to 160 m (e.g. top of Leprédour island), which preclude a marine origin. They are here associated with vertisol resulting from the tropical weathering of different sulphide bearing units, mainly basalts of the Poya Terrane, Eocene flysch, and Mesozoic greywackes of the basement (Beaudou *et al.* 1983; Latham *et al.* 1978; Tercinier 1963). Gypsum occurs in clay (mainly smectite) as disseminated centimetre petal shaped crystals or as large sand roses, and may constitute more than 50 % of the volume of the host soil (Le Berre 1990b, 1991). Detailed studies have placed these occurrences in their pedogenetic and geomorphological context (Podwojewski 1988, 1992, 1993, 1994, 1995). Thick Ca- and Mg-rich vertisols are developed in low relief areas, mostly on hillside, where their thickness may reach 10 m, and occasionally on alluvial formations, down to a depth of 0.8 to 1.5 m. Carbonate (calcite, aragonite, magnesite) concretions are also present in the deposits. In Baie de Saint Vincent, the gypsum-bearing vertisols are capped or replaced uphill by caliche in a paleo-morphological continuum.

These deposits have been operated in many places as open cuts of c. 0.2 km², for a depth of a few metres, mostly manually. From 1917 to 1954, c. 325 000 t was produced solely for use in sulphuration in the nickel smelting process of the Doniambo plant.

The sulphur isotopic ratio ³⁴S/³²S was used as a tracer to identify the origin of the gypsum (Podwojewski 1994). This study found that the isotope ratio of the gypsum is clearly unrelated to the nature of the bedrock. There is a linear anti-correlation between the ratio values of gypsum in the vertisols and the distances from the coast. A dual origin for the sulphur of gypsum from the vertisols was therefore suggested. Near the shore, isotopic ratios are typical of sea water suggesting that a major fraction of sulphur is likely brought by sea spume penetrating the vertisols through cracks opened during the dry season. The ratios decrease inland at the expense of a minor continental source whose signature does correspond to the disseminated sulphur of the bedrock. Various Ca-Mg nodules of the vertisols have been dated by ¹⁴C methods. The main peak age between 15 000 and 28 000 yr BP suggests that the majority of vertisols with gypsum was formed during the last glaciation, under a climate with contrasted seasons, with alternating dry and wet annual periods, and strong winds bringing sea spray (cf. chapter 7, this memoir).

Barite

Barite nodules are often present in the Late Campanian to Maastrichtian Black Chert Formation of the Late Cretaceous post-rift cover. The barium content of the chert is everywhere abnormally high and commonly in excess of 1000 ppm (Maurizot 2011), a fact that has been reported for the equivalent Whangai Formation, in New Zealand (300 to 10 000 ppm Ba; Ballance 1993).

The only occurrence of barite that could be described as a deposit is located in the HP-LT Eocene metamorphic complex of the North of New Caledonia, on Tanlaï Island (Fig. 10), within the Black Chert Formation. Primary barite occurs in a vein stockwork, sometimes as millimetric to centimetric euhedral prismatic or cockscomb crystals, associated with quartz. Part of the deposit corresponds to a secondary concentration as colluvium. The overall deposit has been estimated to c. 50 000 t at 60 % of BaSO₄ and 40 % SiO₂ (Eberlé 1982; Espirat & Millon 1971; Routhier 1953).

Barium as barite in the Black Chert formation is clearly strata-controlled at large scale as shown by its regional extent throughout New Caledonia and New Zealand in the same stratigraphic horizon. There is no contemporaneous volcanic activity. Occurrences are associated with anoxic, organic rich sedimentation during periods of minimal clastic input, typical of this period of post-rift thermal relaxation (Maurizot 2011). A sedimentary origin is therefore inferred. According to the model of Koski & Hein (2003) barite precipitation is controlled by ocean circulation, biogenic productivity, and oxic/anoxic-water boundary. Barite dissolves in anoxic bottom waters and precipitates above the oxic/anoxic-water boundary along submarine slopes. Secondary controls might be necessary to re-concentrate barium in order to form higher grade economic deposits, e.g. faulting or folding in a metamorphic context (which is probably the case in Tanlaï Island deposit). As yet poorly investigated the interest for these minor barite deposits might be renewed by the possible occurrence of accompanying rare earth elements.

Phosphate

Phosphate is the only onland Loyalty Islands mineral resource of interest. The soils of Grande Terre being often magnesian-rich and carbonate-poor, due to the widespread occurrences of ultramafic lithologies, phosphate fertilizer has been massively imported in the past and the exploration of local sources has been accordingly encouraged.

Small scale phosphate occurrences filling karstic dissolution voids and fractures, are very common in the carbonate platform of the Loyalty Islands (Koch 1957a, 1958c). This feature contributes to the higher soil fertility of these islands as compare to Grande Terre. However, phosphate deposits of actual or potential economic interest are only known in Tiga, a small island located between Maré and Lifou, and Walpole, the southernmost emerged land of the Loyalty Ridge (Fig. 10).

The Tiga deposit was discovered during the 1950s. It has been carefully prospected and evaluated, but remains unexploited (Koch 1957b, 1958a, b; Obellianne 1958). Tiga is a 6 x 2.5 km emerged ancient atoll with well preserved morphology, including an elevated crown representing the peripheral reef barrier rimming two stepped plateaus which represents the bottoms of the former lagoon. The phosphate deposit lies in the higher and easternmost plateau. Phosphate occurs as concretions and speleothem fillings and is associated with bioclastic and oolitic limestone. Phosphate lies in a number of karstic voids separated by pinnacles of limestone. Karstic voids are pockets, funnels, deep cylindrical chimneys with vertical walls, complex lobate pits corresponding to coalescent chimneys, and fracture controlled furrows, 2 to 10 metres deep. Most of void morphologies and alignments are fracture-

controlled with a NW-SE direction. Two kinds of ore are distinguished. i) A bioclastic and oolitic limestone which is commonly a soft material that can be excavated manually. Its content is less than 55 wt % P_2O_5 with a high variability. ii) A richer phosphate material comprising amorphous cryptocrystalline collophane nodules and grains mixed with pisoliths and ooliths, in a sandy iron and phosphate rich matrix, which fills the karstic voids. Fish teeth and turtle bones are common in this lithology. The grade is commonly over 70 wt % P_2O_5 .

The ore grade increases toward the center of the Tiga eastern plateau. The reserve, considering the soft material, are of 350 000 to 400 000 t of phosphate ore at a grade of 50 to 75 wt % P_2O_5 and 5 to 20 wt % Fe. Pure collophane nodules represent 20 000 t at 78 wt % P_2O_5 (Obellianne 1958).

On Walpole island (3.5 x 0.6 km) a phosphate deposit of the same type is known with collophane-bearing ore filling karstic voids (Habault 1987; Maurizot & Lafoy 2003). First extractions started as soon as 1888 and continued intermittently until 1914. Operations were hampered by the remoteness and isolation of the island, the lack of fresh water, and the difficulty for a ship to dock. Hand-extracted production is estimated at 160 000 t of exported ore at a grade of 55 – 65 wt % P_2O_5 . A substantial remaining resource is estimated at 400 to 500 000 t (Delvinquier & Jegat 2001).

A small production of phosphate has also been reported from the islands of Huon and Surprise Reef at the northernmost continuation of the Grande Terre (Faivre *et al.* 1955; Paris 1981). In the Chesterfield Islands area small occurrences are reported on Ile Longue (Koch 1957d), however, subsequent general prospecting by drilling failed to find any resource (Rossfelder 1986).

In all the Loyalty Islands deposits, economic or not, phosphate is associated with shallow marine (oolitic) sediments and freshwater deposits (speleothems) developed in reefal carbonate platform environments. Sea level variations, either eustatic or tectonic, are responsible for the development of a karstic morphology and phosphate concentrate in voids. Phosphatogenesis in the many so-called “high islands” of the Pacific has been a matter of debate. The guano model (i.e. accumulation of seabird excrements) has been long abandoned (although fish bone occurrence is an argument for this model) and a marine origin is favoured. For some authors, phosphorus could be volcanogenic, brought to the atolls by abundant stranded pumices or ash falls, since their geochemical signature is found in the bauxitic and phosphate deposits (Bourrouilh - Le Jan 1989, 1992, 1996; Tercinier 1971, 1972). Alternatively, phosphorus from the seawater is essentially bioaccumulated (Montagionni 1985). In the endo-upwelling model the geothermal heat flow provided by underlying volcanic substrate, drives phosphorus enriched deep oceanic water, penetrating through porous reef carbonates into the closed lagoon (Fikri 1991; Rougerie & Wauthy 1989), followed by biogenically controlled massive precipitation of phosphate (Jehl 1995; Rougerie *et al.* 1997). This hypothesis is supported by trace and REE patterns in phosphate indicating both oceanic and basaltic sources (Bernat *et al.* 1991).

Aggregate minerals

Aggregate material supply (sand, gravel, crushed stone, and rip rap) have always been an issue in New Caledonia. This situation result from a non-steady economic growth with sudden phases of development (e.g. world class mining project since 2000's), and strong environmental constraints. Apart from the major mining projects, the main demand and supply are centred on Nouméa, and scattered along the south-western coast (Fig. 11). In 2014, c. 1.4 Mt of materials, all types, have been extracted ([//dimenc.gouv.nc/mines-et-carrieres/les-carrieres](http://dimenc.gouv.nc/mines-et-carrieres/les-carrieres)) in the country, in no more than 10

industrial quarries. Estimate demand for aggregate in 2025 is assessed to 2 to 3 Mt (Lebret & Maurizot 2007).

Geological constraints are pregnant. The variety of available material is restricted. In the Loyalty Islands (cf chapter 6, this memoir), 100 km away from Grande-Terre, limestone is this only available material. On Grande Terre, the presence of Natural Occurring Asbestos (NOA) in many geological units is a major issue. Although there is no mineable concentration of asbestos in the country, NOA is a health concern which is taken into account by authorities. At last, the ubiquitous weathering, specific to the tropical areas, lowers the mechanical properties of all rocks, and bring further complexity in exploration as well as exploitation phases. Regions like the northern and eastern part of Grande Terre are devoid of any suitable aggregate resource because their geological environment is made of schists and ophiolitic melange potentially asbestos-bearing.

Fig. 11 Simplified geological map of New Caledonia showing aggregate potential and NOA bearing units (red frame), and main quarries producing aggregates (2016) with punctual indications on lithology or geological formation operated.

Exploitation of sand and gravel in main rivers is declining or is restricted to specific areas, and will be likely prohibited in the near future, due to the ubiquitous presence of ultramafic-derived detrital rocks potentially NOA-carrying, and in order to protect water resource as well (Garcin 2009, 2010; Garcin & Lesimple 2013b, a).

Materials from the lagoon, although they were prospected or even locally exploited during the 1990s (Maurizot & Bouysse 1989) are nowadays no more conceivable as a resource. Part of the lagoon is designated since 2008 as a UNESCO world heritage protected area.

Exploitation of ultramafic rocks (serpentine and peridotite) as aggregate for concrete or sealing roads, is forbidden, and construction works in ultramafic environment is strictly controlled (2010-4553/GNC act including maps of NOA bearing geological units, www.juridoc.gouv.nc). More than one third of the area of Grande Terre consists of ultramafic rocks and it is not possible to go a few kilometres across the main island without cross cutting an ultramafic formation. NOA occurrences and related health issues (lung cancer, malignant mesothelioma) in New Caledonia are known since the 70s (Goldberg 1994; Goldberg 1991; Goldberg 1995; Goldberg *et al.* 1995; Lessard 1978; Luce 2000; Luce *et al.* 2004). Serpentine, which is a rather good material, due to its mechanical properties, easy to quarry, and generally not weathered, has been widely used by the past, for sealing tracks inside the country. Strong evidences were provided that this material for road surfacing was a major environmental risk factor for mesothelioma in New Caledonia (Baumann 2011; Baumann 2012, 2015; Baumann *et al.* 2007).

Given these constraints, the main remaining targets for crushed stones are volcanoclastic rocks and lavas. Also greywackes of the basement are widely exposed their remote localisation, mainly in the Central Chain, did not favour their exploitation. Around Nouméa the main quarries have been opened in the Late Cretaceous lavas, either basalt, andesite, or trachyte (cf. chapter 4, this memoir), in the greywackes of the Central Terrane (cf. chapter 3, this memoir), and in the Eocene volcanoclastic turbidites (cf. chapter 4, this memoir). The relative thinness of Late Cretaceous lava flows (some tens metres) makes the monitoring of operation rather complex. Contamination by interlayered sedimentary rocks is an issue. Basalts of the Poya Terrane is quarried near to Koné. The Creek Aymes Limestone (cf. chapter 4, this memoir) at the base of the Eocene Flysch is exploited near Bourail.

Clays

Clay occurrences in New Caledonia are mostly of weathering origin. Consequently most of accumulations are discontinuous, with a high variability, and contain impurities or unweathered fragments of bedrock. In 2016, there is still no exploitation of clays in the country. An assessment of the resource has been anyway attempted in the 90s (Le Berre 1990b, 1991). The weathering profiles (cf chapter 7, this memoir) which have been prospected are lying on the Late Cretaceous argillites and mudstones, the cumulate gabbros of the Peridotite Nappe at Mouirange, the Boghen Terrane, and the Poya Terrane. Some potential sources and use may be mentioned.

On argillite and schists, the lateritic part of the weathering profile does not exceed 3 m in thickness, as a ferruginous red clay. In the early times of colonisation, these horizons have been exploited in the Mont Dore area, and a brick factory was build up for local buildings. Although discontinuous and thin, the weathering profile on schists of the Boghen Terrane pertains to major palaeosurfaces with an extent of several tenths of km² that may compensate this discontinuity. Clays are composed of a mixture of kaolinite, gibbsite, metahalloysite, and smectite, with goethite and haematite. Al₂O₃ content is commonly wt 20 %, and may reach locally c. 30 %. This material could be suitable in local use for handmade brick, however this is not a traditional material for constructions.

Kaolinite and gibbsite rich deposits are associated with cumulate gabbros of the Peridotite Nappe. The best exposed and easily accessible occurrences are located in the area of Mouirange. A rather pure deposits of kaolinite, 10 m thick, is located in the Rivière des Pirogues watershed. The lower part

corresponds to 'in situ' weathering profile on gabbros. The upper part corresponds to reworked sediments at the base of the Fluvio-Lacustrine Formation. This material is more appropriate for ceramic.

Clays, as vertisol bearing gypsum, may reach 3 m in thickness on some areas of the Poya Terrane, on the south-western coast. They are mainly composed of swelling clays with a content of c. wt 15 % Al_2O_3 , and is not suitable for construction material.

Dimension stone

The principal rock types that can be used as dimension stone have been investigated in the 1980s and 1990s (Colleau 1984; Le Berre 1991; Paris 1982). Only one exploitation was attempted near Koumac, where two quarries have been operated for some years, with government financial support, in the Paleocene micrite and the Early Eocene pink calciturbidite. This last rock type yielded a pink "marble" (Maurizot 2011) that passed normative tests, had technical and industrial requirements, and was suitable as a commercial product (Maurizot & Le Berre 1991, 1992). It was used locally in a few buildings, and however never exported.

Limestone for cement or neutralizer

The main limestone formations of New Caledonia are:

- on Grande Terre, the Palaeocene micrite (cf. chapter 4, this memoir), the bioclastic limestone at the base of the Eocene Flysch (Middle Eocene Creek Aymes Limestone, Late Eocene Uitoé Limestone, cf. chapter 4, this memoir), the Miocene Népoui limestone (precisely the Wharf Member of the Upper Népoui Limestone, cf. chapter 7, this memoir).
- In the Loyalty Islands (cf. chapter 6, this memoir) which are entirely made up of reefal and bioclastic limestone, huge resource of reefal limestone is available.

Limestone formations have been prospected for cement use in the 90s (Le Berre 1990a), in order to lower imports of clinker in the country, and as neutralizer in order to buffer the acid effluents of the hydrometallurgic nickel industry, since the 2000s.

Palaeocene limestone is not a suitable material for cement due to a high SiO_2 content, presence of cherts, and hardness of the rock. The Miocene Népoui limestone has been investigated by core drills (Le Berre & Maurizot 1992; Noël 1992), with favourable preliminary results that were not followed up. The Eocene limestones have not been investigated.

For neutralizer purpose, the requested material is a pure limestone ($> 95\% \text{CaCO}_3$) with very low Mg content. The Népoui Limestone has been investigated by core drills (Tessarolo 1997). The limestone beds are alternating with laterite and Mg-rich ultramafic-derived weathering products and that material revealed to be unsuitable.

Whatever be the purpose, cement or neutralizer, the Loyalty Islands present huge resource of limestone, however the remoteness from the centres of consumption, all located on Grande Terre, and the environmental as well as societal constraints are not to be underestimated. Limestone outcrops with karstic caves that may contain human remains are protected and sacred places in New Caledonia.

Gemstones

Jade is a relatively common rock in ophiolitic terranes. The semi-precious stone is formed by a monomineralic assemblage of thin tufts of tangled and twisted fibers forming a dense thatch resulting from crushing and recrystallizing under ultramylonitisation conditions. Owing to this structure, it is a very tough rock with a hardness of 6 to 7 on the Moh scale. « Nephrite jade » is constituted by an assemblage of amphibole of the tremolite - actinolite series. « Jadeite jade » is constituted by the sodic pyroxene jadeite. The term semi-nephrite (Turner 1935) applies to incompletely crushed rocks with relict porphyroclasts.

Jade

Jade (*sensu lato*) is a relatively common rock in ophiolitic terranes. The semi-precious stone is not the pyroxene jadeite mineral but is a monomineralic assemblage of thin tufts of tangled and twisted fibres that form a dense thatch. The exact conditions of formation are speculative but may have taken place under ultramylonitisation conditions. Because of the twisted fibre structure, it is a very tough rock with a hardness of 6 to 7 on the Moh scale. Chemically and mineralogically, nephrite jade is an amphibole of the tremolite - actinolite series. Jadeite jade is constituted by the sodic pyroxene jadeite. The term semi-nephrite (Turner 1935) applies to incompletely recrystallised rocks with relict mineral porphyroclasts.

Jade in New Caledonia is more important from an archaeological and heritage point of view rather than from a business and economic perspective. Like other Pacific Island populations, the first inhabitants of New Caledonia have known and used the jade as tools or as ritual objects. In the objects collected by archaeologists (ceremonial axes, pearl necklaces, adzes) many are made from either serpentinite or jade. Ouen Island is the most oft-cited source of jade (Lacroix 1942) but it is likely that other sites were discovered by the Kanak, most of the locations now being unknown. The geological units of New Caledonia that may provide jade are: i) The Boghen Terrane, a Mesozoic HP-LT metamorphic subduction complex, where nephrite occurrences are found at the serpentinite-schist contact (cf. chapter 3, this memoir). ii) The Eocene HP-LT metamorphic Pouébo Terrane of northern New Caledonia. In principal, crystalline jadeite jade (*sensu stricto*) could exist here but it has not yet been discovered (cf. chapter 5, this memoir). iii) The Peridotite Nappe where various gabbros, either dykes or cumulates are often highly sheared and mylonitised (cf. chapter 5, this memoir).

Several nephrite jade sites have been studied to varying degrees, and have been permitted for occasional contemporary extraction.

Ouen Island is certainly the best known and most studied site. The rock is a semi-nephrite with pyroxene porphyroclasts and has no or very low commercial value. It is possible that in the past more substantial blocks of better quality nephrite were collected by the Kanak, but no trace now remains.

The Rivière Bleue occurrence consists of alluvial pebbles and cobbles in this large river. The primary source upstream is not known.

The Rivière des Pirogues jade occurrence was worked for a few years in the 1990s. The host rock typically consist of highly sheared basic dykes cutting through the Peridotite Nappe, belonging to the 53 Ma intrusives (Cluzel *et al.* 2006). The quality of the jade varies from semi-nephrite to pure nephrite. The in situ dykes are naturally dismembered by the stream. The pebbles and cobbles, cleaned by the current, driven downstream over several kilometres, were simply collected in the river bed.

In summary, for the currently known occurrences in New Caledonia, nephrite jade does not occur in massive and consistently good quality *in situ* lenses. There is a small, local arts and crafts market in "Caledonian jade" but nothing like the status of true jade on the international gemstone market.

Chrysoprase

Silica leached during the weathering of ultrabasic rocks may precipitate as more-or-less well crystallized products corresponding to an intimate mixture of quartz, chalcedony, and opal. They are variously coloured by inclusions such as iron oxy-hydroxides, serpentines and/or Ni bearing phases. Green varieties of silica veins, coloured by nickel (Hatipoglu *et al.* 2011), are called chrysoprase (green chalcedony) and prasopale (green opale), and are of gemmologic interest.

"Chrysoprase" is reported from several places in the Peridotite Nappe, as veinlets at and below the base of weathering profiles. Specific tenements have been granted in the past in the Ouaco area but none is still presently valid. The major phase is an Opal-CT with minor opal-A, and inclusions of sepiolite and paragonite. The Ni content is of 0.3 to 6.4 wt %. The deepest green colour corresponds to the higher Ni content (consultancy reports, SGNC). The strict term prase-opal would better apply to this material.

Chrysoprase (*sensu lato*) is used occasionally for local arts and crafts where it is often confused with jade. New Caledonia material is not known on the international gemstone market and the very limited production is not exported.

Hydrocarbons

Coal

Coal in New Caledonia is found in the Late Cretaceous "Formation à charbon" as seams and lenses 1 to 2 metres thick and 10 to 50 metres long (cf. chapter 4, this memoir). These were discovered and described in the early times of European colonization (Garnier 1867a; Heurteau 1876).

Coal potential was actively investigated in the 1950s (Espirat 1957, 1958; Koch 1957c; Noesmoen 1957a, b, 1959a, b; Pomeyrol 1952). The coal measures are generally the uppermost beds of fining upwards flodd plain successions (conglomerate, cross bedded sandstones, mudstone, coaly mudstone, coal) typical of fluvio-deltaic environments of that syn-rift period. Coal beds are strongly tectonised by disharmonic folding and thrusting, mechanically weak coal horizons preferentially localising detachments. Coal seams may locally reach several metres thickness by strutral hinge thickening but conversely may pinch out rapidly.

The main areas prospected by trenches, pits, galleries, and drills are located to the NW of Nouméa, and near Moindou and Voh. The only significant mining of these deposits took place near Moindou on the west coast between 1924 and 1930, where c. 77 000 tons of coal were produced and used in the first nickel smelters in Nouméa. However, the tectonic complexity has prevented any profitable mining exploitation of this resource, and by 1930, it became clear that, due to the poor quality of the coal, and the high cost of its extraction, it could not compete with other imported, mainly Australian, coke.

Nowadays, coal of the "Formation à charbon" is considered as a potential hydrocarbon source rock for an offshore New Caledonian oil and gas resources. This is by analogy with the Late Cretaceous Rakopi Formation (Killops *et al.* 1994) of NW New Zealand which is the source rock for the productive offshore

Taranaki Basin (Cook 1987; Herzer *et al.* 1999, and other references in Hydrocarbon section, this memoir).

Oil and gas

Oil and gas shows have been known since the beginning of the 20th century in the western part of the Grande Terre. The Late Cretaceous to Eocene cover (cf. chapter 4, this memoir) has been considered as a potential petroleum system and, as such, the Nouméa and Bourail area were explored during the 1950s (Pomeyrol 1951; Tissot & Noesmoen 1958). In the 1970s several oil companies obtained seismic exploration permits offshore New Caledonia. The associated surveys revealed fairly thick sedimentary series in the basins surrounding New Caledonia (Ravenne 1982). In the beginning of the 1990s the *ZoNéCo* research program was launched to evaluate the natural resources of the EEZ of New Caledonia. A generation of modern data were then acquired, providing new insights onto the geometry and nature of known basins and allowing a renewal of interest for offshore hydrocarbons in the 1990s (France 2000). Since then, even more data have been acquired but, in a global context, the area remains very poorly explored and is considered a frontier area (Sutherland *et al.* 2012).

Onshore

Direct Hydrocarbon Indicators (DHIs) are crucial elements in assessing petroleum potential. In Nouméa, a drillhole was bored, in 1909, near Ouen Toro, close to known oil seeps in Paleocene Limestone (Haas 1932; Maurizot & Gasc 1986). The well reached a depth of 423 m, crosscutting the Eocene Flysch and various olistoliths. Small quantities of gas were expelled and ignited, however, given that it is now understood that the hole was drilled into accretionary prism strata, an olistostrome, and probably a large olistolith, it was very unlikely to find any appreciable hydrocarbon reservoir.

Oil seeps were discovered in the 1910s, in northern New Caledonia, to the south of Koumac village, at a place today known as “La Mine d’Huile” (Oil Mine). These seeps are found in a rather unusual location within the serpentinite sole of a small peridotite klippe which overlies the Poya Terrane basalts. The area was first explored by a few shallow pits and a gallery. From 1914 to 1918 and in 1954, drilling down to 185 m depth, was carried out along a NE-SW section (Pomeyrol 1951; Vially & Lafoy 2008). The drilling revealed two oil shows in the serpentinite. Unfortunately, oil dilution in the water and contamination by organic matter, precluded recovery of enough material for confident analyses. The only substantial conclusion was the natural character of the oil. This unusual natural seepage in an allochthonous ultramafic terrane indicates that oil generation did take place, and that the oil probably had a long and complex migration pathway from an unknown sedimentary source rock. According to Vially & Mascle (1994) the source rock could be coal measures located in a Cretaceous basin overthrust by the allochthons.

The Bourail Anticline (Pomeyrol 1951; Tissot & Noesmoen 1958), involves a succession of Eocene turbidites, c. 4 km thick, overlying Late Cretaceous to Palaeocene series. The anticlinal axis is 25 km long and dips northwestward to form a pericline in the Montagnes Blanches area (Maurizot 2014). This simple structure, potentially a classic hydrocarbon structural trap, was identified as a target for petroleum exploration in the 1950s. Several exploration boreholes were therefore drilled near the anticlinal axis. Boreholes Gouaro-1 (608 m) and Gouaro-2 (441 m) were drilled in 1954 and 1955, respectively (Pomeyrol 1955); both remained in the Eocene Flysch (Paris 1981). Gouaro-1 crosscut some gas showings. A more recent campaign (France 2000) also targeted the Bourail Anticline. It consisted of a seismic reflection survey (Blake 1996), and a 1930 m-deep exploration borehole (Cadart-

1), almost entirely core-drilled in 1999 (Maurizot 2005). It recovered a significant interval of the Eocene Flysch and reached the uppermost part of the Late Cretaceous formations. Significant gas shows were encountered and ignited, while oil inclusions were observed in some calcite filled fractures within the Eocene Flysch. This borehole, the deepest ever drilled in New Caledonia, therefore provides a unique data set for the understanding of the island's geological framework and evaluation of its petroleum potential.

Hydrocarbon system model

These tiny onshore New Caledonia showings demonstrate that a hydrocarbon system existed (Vially & Lafoy 2008) and likely has a continuation offshore.

The inferred system is similar to that of New Zealand which is today productive and actively prospected. In the onshore New Zealand region, Taranaki Basin is New Zealand's only productive hydrocarbon gas-rich basin (King *et al.* 1999; King & Thrasher 1996; Uruski 2008). Late Cretaceous carbonaceous sandstones and mudstones, typically associated with coal measures, of the Rakopi Formation, are the source of most of the oil. Rakopi Formation extends offshore mainly in the Taranaki Basin (Killops *et al.* 1994), and a correlative has also been dredged on the western flank of the West Norfolk Ridge (Herzer *et al.* 1999). In New Caledonia, Late Cretaceous coal measures are also likely source rocks but the reservoir and seal are different from Taranaki Basin. The fractured sandy Eocene turbidites are suspected for the reservoirs, and shaly Eocene turbidites for the seal (cf. Bourail Flysch, and chapter 4, this memoir).

Offshore potential

The offshore area between Australia, New Caledonia, and New Zealand has been called the Tasman Frontier (Sutherland *et al.* 2012). It is a vast under-explored area in the southwest Pacific predominantly underlain by submerged continental crust, and corresponds to the northern part of Zealandia as defined by Luyendyk (Luyendyk 1995; Mortimer 2008). It hosts several large unexplored sedimentary basins that share a common origin with producing basins such as the Gippsland and Taranaki basins respectively in Australia and New Zealand. Although no exploration drilling has taken place in northern Zealandia other than in the Taranaki Basin and vicinity, this vast area offers a wide range of potential petroleum prospects. The only existing drilling data in the region are from the Deep Sea Drilling Project (DSDP) carried out during 1971–1973 and in 1982 (Burns & Andrews 1973; Burns *et al.* 1973). During the 1990s and early 2000s, data acquisitions, including reflection seismic, gravity, magnetic, multibeam bathymetric information and rock dredge sampling, have been driven by government initiatives and UNCLOS (United Nation Convention on the law of the sea). This provides a useful framework for petroleum exploration in the different EEZ. Together, these data represent more than 100 000 km of profile and are gathered in the publicly available Tasman Frontier Database (Sutherland *et al.* 2012).

Fig. 12 a) Bathymetric map showing positions of all publicly available seismic lines of the *Tasman Frontier Database* (TFDB, Sutherland *et al.*, 2012), Deep Sea Drilling Project (DSDP) wells, petroleum exploration wells and the limits of Australia, New Zealand and France/New Caledonia Exclusive Economic Zones (EEZs). Bathymetric data from Global Predicted Bathymetry V18.1 (Smith & Sandwell, 1997). Red line indicates location of seismic profile GA206-01. b) Seismic

profile GA206-01 across the Fairway Basin (modified after Rouillard *et al.*, 2014 and Rouillard *et al.*, 2015). Seismic stratigraphic units Fw1: Post-rift, Fw2: Syn-rift, Fw3: Pre-Rift. Key to annotations: C: Turbidite channel-fills; D: Diapirs; PW: Prograding wedges; Vertical arrows: Fluid escapes.

Several basin studies including maturity and prospectivity assessments of the Fairway Basin west of New Caledonia have been conducted (Kroeger & Funnel 2011; Vially & Bernard 1999; Vially & Lafoy 2005, 2008; Vially & Mascle 1994). Kroeger & Funnel (2011) reviewed model predictions for the maturity of potential source rocks and volumes of oil and gas expelled, and presented likely migration pathways for charge of potential reservoir structures.

Although several sedimentary basins have a hydrocarbon potential in the wider Tasman Frontier area, New Caledonia petroleum prospectivity assessments e.g. (Exon *et al.* 2007; Kroeger & Funnel 2011; Rouillard *et al.* 2014) have typically focused on the Fairway Basin, mainly due to its relatively good data coverage when compared to nearby basins. Water depths of the Fairway Basin, range from less than 1 000 m to 2 400 m. Previous studies conducted on this basin have revealed a sedimentary cover greater than 3,000 m in thickness (Ravenne *et al.* 1977). The basin contains an inferred near-complete Cretaceous-Cenozoic sedimentary cover which comprises deeply buried Cretaceous stacked deltas (Rouillard *et al.* 2015). The basin probably formed in the late Early to Late Cretaceous, during eastern Gondwana breakup, and has received detrital and pelagic sediments since that time (Exon *et al.* 2007; Lafoy *et al.* 1994; Rouillard *et al.* 2015). Recent wide-angle refraction seismic studies revealed a 15 km-thick continental crust beneath the basin (Klingelhoefer *et al.* 2007). More than 100 diapirs have been mapped within the sedimentary column and a bottom simulating reflector (BSR) has been identified across an area of 70,000 km² (Auzende *et al.* 2000a; Auzende *et al.* 2000b; Auzende *et al.* 2000c). This BSR was initially interpreted as being the world's largest gas hydrate field, but subsequent re-interpretation from high-resolution refraction seismic data and heat flow measurements suggested that the reflector was related to an opal-A to opal-CT diagenetic front (Nouzé *et al.* 2009).

When considering the structural continuity with the Taranaki Basin of New Zealand (Collot 2009; Collot *et al.* 2009), the above observations and interpretations form strong evidence for the petroleum potential of the Fairway Basin.

Thermo-mineral springs

Two types of warm springs are known in New Caledonia. On the eastern coast, several small springs are scattered between Thio and Canala. In the south of Grande Terre hyperalkaline springs are found in the ultramafic Massif du Sud (Fig. 13). Both are of low enthalpy type and present low rates of flow and thus a weak potential in term of geothermal energy.

Fig. 13 Thermo-mineral springs of Grande Terre, New Caledonia.

East Coast springs

The springs are distributed over a 30 km zone roughly parallel to the east coast, below the basal thrust sole of the Peridotite Nappe. The springs emerge from either the autochthonous basement or the Poya Terrane, and always in the vicinity of serpentinite slices or listwanite. Gas bubbling can be observed at many of the springs, and as previously noted (Cox *et al.* 1982), most of these springs are in topographic lows, close to a river, or in river bed. The main springs are located at La Croûen where thermal baths have been located in the past (Koch 1958d). In this area fourteen small low temperature seepages are located along the river and discharge in it.

Some characteristics of the waters are given in table 3. When the flow is low, the temperature of the spring waters is close to ambient. All of them have a sulphurous odour. All have the same composition of Na-HCO₃-Cl-SO₄ type and pH values are either neutral or slightly alkaline. Stable isotopes of oxygen and hydrogen indicate a meteoric origin of these waters (Cox *et al.* 1982). Many of the springs deposit white precipitates (likely chalcedony according to Cox 1982) associated with filamentous algae (Avias 1949; Cox *et al.* 1982).

A speculative relation has been attempted between the present-day thermal springs and the sulphur occurrences of the post-obduction Sb-Au-As-Hg deposits or listwanite (cf. Post-obduction magmatism,

this chapter), although these mineralisation is associated with the much older Late Oligocene granodiorites (Cox *et al.* 1982).

Name	T° C	Flow l/s	pH	Conductivity (μS/cm)
La Crouen	40 - 43	3	8	250
La Crouen (small seepages)	22 - 27	< 0.1	8	
Gelima	29	< 0.1	9	
Karangué	Ambient	< 0.1		550
Fanama	32	0.5	8	
Pont de Mokoué	28	< 0.1	8	
Kopélia	Ambient	< 0.1		

Table 3. Some characteristics of the East Coast thermo-mineral springs (Cox *et al.* 1982; Paris 1981, and this work).

Hyperalkaline ultramafic related springs

Several hyperalkaline springs are known in the Peridotite Nappe of the Massif du Sud. These are both onshore and underwater. In the southern lagoon, the most famous is in the Baie de Prony, where it is responsible for the formation of the well-known Aiguille de Prony. Several other springs have been found on land in river beds (Fig. 13). The Baie de Prony hydrothermal field was extensively studied during the HYDROPRONY cruise (Oct-Nov 2011). In the Baie de Prony, one of the springs is on land above sea level (Rivière des Kaoris), one is in the tidal zone and uncovered at low tide (Bain des Japonais), and several are underwater in the lagoon. In the middle of the Baie de Prony, the Aiguille de Prony, known since the 19th century (Garnier 1871), is a pinnacle towering 35m above the seafloor, with its summit 2m below sea level (Launay & Fontes 1985). A recent bathymetric survey of the seafloor of the bay has revealed the existence of other submarine hydrothermal formations, at water depths between 30 and 50 m (Pelletier *et al.* 2006). The springs are characterised by precipitation of carbonate forming travertine terraces, low temperature, low salinity, gas bubbling, and high pH. Contrary to what is commonly reported, these springs are not correlated with obvious serpentinitised fault zones. No correlation between the spring locations and tectonic features like faults has been demonstrated so far. Instead they occur in the vicinity of rivers.

Waters collected at these springs are of the Ca-OH type (Monnin *et al.* 2014) and are characterized by very high pH values (up to 11.2), a low salinity (even those located in the lagoon) which is indicative of their meteoric origin, and common bubbling of H₂ and CH₄-enriched gases (Monnin *et al.* 2014). These hyperalkaline hydrothermal fluids result from present day serpentinization reactions (Barnes & O'Neil 1969), involving aqueous alteration of Fe and Mg silicates of peridotite (olivines and pyroxenes). It involves dissolution of primary minerals, and precipitation of secondary serpentine, magnetite, and brucite. The oxidation of metals (mainly iron and to a lesser extent, nickel) contained in the olivines and pyroxenes and the reduction of water, produce a H₂ enriched gas phase and very alkaline fluids. Further reactions of hydrogen with either organic matter or oxidized carbon compounds may lead to the formation of abiogenic methane (Chavagnac *et al.* 2013; Chavagnac *et al.* 2014). In the Baie de Prony hydrothermal field, mixing of the hydrothermal end-member with the lagoon water is responsible for the precipitation of brucite and Ca-carbonates that can accumulate either as platforms uncovered at low tide (Bain des Japonais) or as underwater masses (Aiguille de Prony).

Some of the characteristics of hyperalkaline springs in the Massif du Sud are given in table 4.

Onland, mixing of hyperalkaline fluids with surface freshwater leads to the precipitation of dominant calcium carbonate whilst offshore, brucite is dominant. Gas bubbles at Bain des Japonnais and Rivière des Kaoris contains between 12 and 30 volume % hydrogen in dry gas, 6 to 14 % of methane, and 56 to 72 % of nitrogen, with trace amounts of carbon dioxide, and other hydrocarbons (Monnin *et al.* 2014). The Aiguille de Prony hosts chemolithotrophic microbial communities adapted to the hyperalkaline environment (Ben Aissa *et al.* 2015 ; Quéméneur *et al.* 2014).

The Baie de Prony hydrothermal field is an example of a serpentinizing environment (Schrenk *et al.* 2013) and shares common characteristics with the Lost City Hydrothermal Field near the mid-Atlantic Ridge (Kelley *et al.* 2001). Because of its accessibility, Baie de Prony could become a privileged laboratory to address fundamental questions related to the study of low temperature serpentinization, such as the alkaline hypothesis for the origin of life, the subsurface CO₂ storage by peridotite carbonatisation, the long term alteration of natural cement analogues and its consequences for the storage of radioactive waste, the extension of the biosphere in the ocean floor and in the mantle, the geological history of seawater and methane production in ultramafic formations exposed at the surface of Mars.

Name	T° C	Flow l/s	PH	Conductivity (μS/cm)
Nord Yaté	24		11.7	
Rivière des Rochers	26		11	
La Coulée	30		10.8	281
Bain des Japonnais	37 - 40	0.17	11	
Rivière des Kaoris	32	0.2	10.8	

Table 4 Some characteristics of the hyperalkaline thermo-mineral springs from Massif du Sud (Cox *et al.* 1982; Launay & Fontes 1985; Monnin *et al.* 2014, and this work).

Conclusions

Mineral resources of New Caledonia are the end result of a c. 300 million years of geological and tectonic development in dominantly oceanic to arc settings. There is a clear spatial and genetic relationship between type of mineralisation and specific rock units and paleo-environments.

The only known deposits in the basement are in the crustal part of the Late Carboniferous Koh Ophiolite, as minor VMS-type copper and gold showings. Surprisingly, there are no major exposed VMS type deposits in the partly co-eval Téremba Terrane, even in the seemingly favourable Late Permian arc-related proximal volcanic setting. Within the cover, the Late Cretaceous period of rifting, is particularly fertile. It provided several VMS poly-metallic concentrations like the Diahot base metals, gold and silver SEDEX type deposits, and copper-gold Cyprus type deposits in the Poya Terrane.

Post-obduction granodioritic magmatism gave rise to original mineralisations including mainly Au and Sb at or near the base of the Peridotite Nappe, a major contact at New Caledonia scale.

Most of these metallic occurrences are of little economic interest at present, but the presence of gold in most types should always be taken into account.

Most of non-metallic resources including gemstones have been or are used locally. Even though they are not exported, they can represent significant economic value in the country.

Of interest for the long term, is the oil and gas potential of the New Caledonia EEZ within the wider Tasman Frontier area of northern Zealandia. A viable petroleum system has been demonstrated. This huge playground, in a submerged and complex geological region, will require a substantial effort of future marine exploration, through international programmes, sustained by high level research.

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Illustrations

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