

9.0 MINERALIZATION

9.1 *Laterites*

Cobalt-nickel mineralization in the Geovic deposits occurs within the weathering profile overlying sheared, serpentinized ultramafic rocks, probably dunites. The lateritic weathering profile averages about 20 meters thick, but exceptionally extends to 40 meters near ridge crests or in fracture zones. The mineralized laterite forms lenses which are generally greater than 10 meters thick. The lenses often lie generally parallel to the rolling topography of the Nkamouna plateau. They are relatively smooth on top, but irregular on the bottom, where weathering has penetrated downward into fractures and shear zones in the underlying serpentinite.

Most of the economic mineralization occurs at a single level, with an average of about 1 meter of ferricrete breccia underlain by approximately 4 meters of ferralite. The ore types are characterized geologically by their mineral content, bulk composition, and texture, as described below. The deposits have an unusually large concentration of the coarsely aggregated ore mineral asbolane, thick ferricrete breccia, and abundant maghemite.

9.1.1 Laterite Stratigraphy

The Cameroon laterite profiles, similar to those elsewhere in humid tropical environments, show a strong vertical zonation, which reflects the transition from unweathered host rock at the base, to highly-leached residues at the surface. The Cameroon laterites depart from the norm somewhat, in possessing two layers of iron-rich laterite separated by an iron-rich ferricrete breccia. The laterite under the breccia includes the limonitic ferralite and underlying saprolite zones which are more typical of humid tropical laterite profiles.

The typical sequence of discernable horizons in the weathering profile at Nkamouna is described below in Table 9-1 (modified from Geovic report data) and illustrated in Figures 7-3 and 7-4. The terminology and abbreviations of these units have varied somewhat since 1995, with the currently-preferred terminology being shown first. Further descriptive details about these units are below, modified slightly from Geovic descriptions.

Upper Laterite. (UL). A purplish-red, highly magnetic, powdery clay-like soil. Ubiquitous, normally 4 to 8 m thick, ranging up to 19 meters, except where removed by erosion at the borders of the laterite plateaus. This unit will be easy to excavate for completing test shafts and for mining.

Ferricrete Breccia. Beneath the Upper Laterite is a nearly ubiquitous horizon of ferruginous concretions, ranging in size from pisolites 1-2 centimeters (cm) across, to blocks larger than a meter across. Large blocks have complex structures, characterized by multiple stages of brecciation, with vesicular, tubular structures, and amoeboid shaped cavities. They are composed of agglutinated pisolites and angular ferricrete fragments, with some limonitic matrix. Ferricrete fragments are typically dark red

outside and varicolored on fresh surfaces. Where the blocks were large enough to impede deepening of the test pits, the ferricrete breccia was formerly referred to as "Hardpan" (logging unit HP). The ferricrete breccia averages 6 to 8 meters thick, and was often divided into two or three units by project geologists.

The Upper Ferricrete Breccia (UB) is typically pisolitic and relatively low in Co and Ni except locally where stained with black manganese (Mn) oxides.

Hardpan (HP) is the most highly-cemented ferricrete breccia and is very difficult to penetrate with hand tools. It forms outcrops in some areas, particularly at the borders of the lateritic plateaus, and averages 2 m thick. Where present, it grades upward and downward into UB and LB, respectively.

The Lower Ferricrete Breccia (LB) consists of reddish concretions, with abundant black Mn oxides, texturally similar to UB, with a matrix of Ferralite (FL). It is typically 1-2 m thick, and >2% Co may occur at the base, especially where concretion-like aggregates of asbolane occur. It is hard to dig with hand tools.

Ferralite (FL). Ferralite is a limonitic laterite, sometimes pulverulent, mottled, with varied shades of black, yellow, brown, red. It is often foliated, reflecting relict serpentinite textures. Local maghemite occurs near the top. Thickness varies from a few meters to tens of meters, averaging near 8 m. It is consistently mineralized with good metal grades near the top where black Mn zones occur, moderate to low Co grades lower in the unit. The magnesium oxide (MgO) content is very low, averaging about 0.5 percent, part of which is present as non-reactive MgO in spinel (i.e., magnesian chromite). This unit is easy to moderately easy to excavate for completing test pits and for mining.

Silcrete (SI). This highly-discontinuous unit may lie at the boundary between the Ferralite and the upper Saprolite. It is composed of subhorizontal plates of white to grey silica, intercalated with varicolored clays. Usually 0.5 m thick or less, and often absent. Commonly has low metal contents and is very hard to dig. It is generally interpreted to mark a former water table, and often occurs just above the current water table.

Saprolite zone (SP). This zone is composed of green, sticky clay with less than 50 percent fragments of partly weathered serpentinite, grading downward into foliated, fractured serpentinite. It may have silica-filled steep fractures. It averages 1.5 m thick, is relatively poor in Co, but can be rich in Ni, and is easy to moderate to dig. Saprolite typically contains less than 40 percent Fe and elevated MgO (15-30 percent).

Serpentinite (SE). The serpentinite bedrock is olive green to dark green and may be fractured and fissile, with silica-filled fractures. It has uniformly low metals grades except in rare cases where garnierite-like nickeliferous silicates fill fractures. It is relatively hard and rarely encountered in test pits, but sometimes in drillholes. Magnesium grades are typically greater than 35 percent and iron contents are usually less than 10 percent.

TABLE 9-1
Geovic Mining Corp.
Nkamouna Project, Cameroon
Laterite Stratigraphy

Horizon	Alternate/Former Names	Lithology	Dominant Mineralogy	Approx % Fe	Co Content	Ni Content	Comments
Organic Soil	--	Mainly organic	--	low	near zero	near zero	usually < 15cm, not logged
Upper Laterite (UL)	Upper Clay, Upper Limonite (UL), Granular Zone (GL)	Red, fine-grained, pulverulent to pisolitic	limonite, hematite, maghemite	40-50	low	low	partly magnetic
Ferricrete Breccia (UB, LB,HP)	Upper Ferricrete Breccia (UB), Lower Ferricrete Breccia (LB), Hardpan (HP), Breccia (FB)	Iron oxides; indurated, brecciated, vuggy	limonite, hematite, maghemite, some asbolane	40-50	high near base	low	may contain schist fragments & gibbsite
Ferralite (FL)	Lower Limonite (LL)	Brown, fine-grained,	clays, limonite, hematite, some asbolane	20-35	high near top	high near base	may contain schist fragments & gibbsite
Silcrete (SI)	Transition Zone	Hard, platy silica	quartz, chalcedony, limonite,	10-20?	low	low	usually absent, occurs in LL or SP; old water table?
Saprolite (SP)	Saprolite Clay	Weathered serpentinite, clays, silica	clays, serpentine, silica	10-20	low	high	
Serpentinite Bedrock	Serpentine	Sheared, soft rock	serpentine, silica, talc?	5-10	very low	very low	schist, if present

Water Table. The depth to the water table was recorded in 32 of the Geovic reverse-circulation drill holes. In all but seven of these holes, the water table was between 12 and 25 meters below surface, and was usually within the Ferralite or at the upper limit of Serpentinite. The top of the water table varies seasonally 4-5 meters.

Based on evidence from specific-gravity determinations, assays, and the logged lithologic descriptions, as well as PAH observations, PAH believes that perhaps the lower part of Geovic's "Ferralite" could be described as "Saprolite", since the Ferralite frequently shows relict bedrock textures. However, GEovic geologists suggest that based on chemistry and mineralogy the unit is indeed a ferralite. Similarly, some of Geovic's "Saprolite" would probably be regarded as "Sap-rock," or even "Serpentinite Protolith" in other laterite districts (see Gleeson, et al, 2003, page 13).

The Upper Laterite, Ferricrete Breccia, and Ferralite units contain fragments of schist, or minerals derived from schist, when the laterite is developed over schist inliers within and lateral to serpentinite. The Saprolite unit contains weathered schist fragments when schist forms the local bedrock, making it easy to distinguish schist-derived laterite from ultramafic-sourced laterite.

9.1.2 Laterite Mineralogy

The minerals of economic interest in the Nkamouna laterites are shown on Table 9-2, which incorporates data from various Geovic reports and the PMET report (2002). Of the minerals listed in Table 9-2, most occur in the majority of nickel-cobalt laterites worldwide, in proportions which vary widely from one laterite horizon to another, and from one deposit to another. In general, these minerals occur at Nkamouna as fine-grained clay-like or concretionary masses, and are only occasionally identifiable as discretely visible mineral specimens. One exception is gibbsite, which may occur as mammillary masses or vug-fillings of radiating transparent to milky white crystals several millimeters (mm) long. Of great significance is the size of the asbolane agglomerates and wad that host the cobalt and almost all of the manganese.

Asbolane

Absolane is the key mineral in the Geovic deposits, which hosts the cobalt, most of the manganese, and a significant part of the nickel. Between one-third and one-half of the deposit's nickel is hosted in asbolane (see PMET Mineralogical Report, 2002). This mineral is sometimes referred to as "asbolan" or "asbolite" in the scientific literature, or "wad" or "cobalt wad" as field terms. Asbolane is widespread in nickeliferous laterites, but elsewhere is usually present in very small amounts and is normally inconspicuous as black blebs on fractures. Individual asbolane crystals have hexagonal symmetry, a Mohs hardness of 6, and are very dark in color. Typically, individual crystals are rarely visible to the naked eye or a hand lens; rather the mineral forms blackish patches or crusts on fractures and cavities. The asbolane occurrence at Nkamouna is unusual in that it occurs as both discrete platy crystals and in larger and coarser crystal aggregates and fine-grained wad up to 5 cm in diameter, sometimes as concretion-like nodules with chromite and goethite. It also occurs as a fine intergrowth with Cr and Fe oxides and hydroxides (PMET Report, Nov. 2002).

TABLE 9-2
Geovic Mining Corp.
Nkamouna Project, Cameroon
Selected Minerals in Laterite Profile

Name	Mineral Type	Formula	Origin	Typical %Co	Abundance in Co-rich material	Maximum occurrence
asbolane ("wad")	hydrated oxide-hydroxide	$(\text{Co},\text{Ni})_{1-y}(\text{MnO}_2)_{2-x}(\text{OH})_{2-2y+2x}\cdot n\text{H}_2\text{O}$	weathering	10-15	6%	LB, LL
ernienickelite	hydrated oxide	$\text{NiMn}_3\text{O}_7\cdot 3(\text{H}_2\text{O})$	weathering	low Co, high Ni	reported*, not confirmed	?
"limonite"	oxide-hydroxide	fine-grained mixtures of goethite $\text{FeO}\cdot\text{OH}$, lepidocrocite $\text{FeO}\cdot\text{OH}$, hematite Fe_2O_3 ; others	weathering	0.0X-0.3	60-70%	UL, LL
goethite		see "limonite", above			see limonite	see limonite
hematite	oxide	Fe_2O_3	weathering	0.00X	3% incl maghemite	UL, UB, LB, LL
maghemite	oxide	$\gamma\text{-Fe}_2\text{O}_3$ (ferromagnetic)	weathering	0.00X	incl in hematite	UL, UB, LB, LL
carolite, kerolite, garnierite	silicates, mineraloids	approx formulas $(\text{Mg},\text{Ni})\text{SiO}_3\cdot n\text{H}_2\text{O}$	weathering (rare)	0.0X Co, high Ni	reported*, not confirmed	saprolite
nontronite	silicate clay (smectite gp.)	$\text{Na}_{0.33}(\text{Fe},\text{Ni})_2(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_2\cdot n\text{H}_2\text{O}$	weathering (rare)	0.X, 0.X to X Ni	reported*, not confirmed	saprolite
montmorillonite	silicate clay (smectite gp.)	$\text{Na}_{0.33}(\text{Al},\text{Mg})_2\text{Si}_4\text{O}_{10}(\text{OH})_2\cdot n\text{H}_2\text{O}$	weathering (rare)	low	reported, not confirmed	saprolite
kaolinite	silicate clay	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$	weathering of adjacent schists	0	9% in bulk sample	all
gibbsite	hydroxide	$\text{Al}(\text{OH})_3$	weathering of adjacent schists	0	1%	UL, UB, LB, LL
silica, quartz	silicate	SiO_2	weathering, remobilization	0	5%	saprolite, serpentinite
serpentine	silicate	$(\text{Mg},\text{Fe},\text{Ni})_3\text{Si}_2\text{O}_5(\text{OH})_4$	late magmatic	0.01 Co, 0.3 Ni	<1%	saprolite, serpentinite
talc	silicate	$\text{Mg}_3\text{Si}_4\text{O}_{10}(\text{OH})_2$		0	<1%	saprolite, serpentinite
magnetite	oxide	Fe_3O_4 (ferromagnetic)	magmatic	0.00X	8% (incl. chromite)	all, max in UL
chromite	oxide (spinel)	FeCr_2O_4	magmatic	0	See magnetite	all, max in UL
olivine	silicate	$(\text{Mg},\text{Fe},\text{Ni})_2\text{SiO}_4$	magmatic	0.01 Co, 0.3 Ni	<<1%	rare in serpentinite

There is no theoretical fixed Co or Ni content for asbolane because the formula of $(\text{Co,Ni})_{1-y}\text{MnO}_2)_2 \cdot x(\text{OH})_{2-2y+2x} \cdot n\text{H}_2\text{O}$ allows for substitution among Co, Ni, and Mn to reflect the chemistry of formation waters, and to achieve charge balance. The Co:Ni ratio in asbolane at Nkamouna ranges from 1:1 to 10:1 (expressed as stoichiometric oxides) and averages about 2:1 (PMET, 2002). "Asbolite" from Soroako, Indonesia (Evans, et al., page 46) shows a range of compositions ranging from 2.5 percent Co to 5.8 percent Co, and averaging (in the limonite zone) Co:Ni 3.3:1. The Soroako and PMET analyses also report large amounts of Fe, so it is possible that the samples were not pure asbolane. Analyses of asbolane samples from Nkamouna range from 6.3 to 19.5 percent CoO. The asbolane component of the Nkamouna bulk mineralogy modal analysis expressed as a weight percent ranges from 3.2 to 7.2 percent (see PMET Report, 2002).

Asbolane is critical to the project economics, because it occurs as coarser aggregates of microscopic crystals, the aggregates being separable by crushing and wet screening from the pulverulent iron-oxide minerals and clays. The resulting coarse fraction contains most of the Co and Mn, and a significant portion of the Ni in the raw material, resulting in a significantly upgraded concentrate (3.1x for ferrallite unit) prior to leaching.

Clay Minerals

Kaolinite is the most abundant clay mineral at Nkamouna (see Table 9-2). The PMET report (2002) presents bulk samples of potentially processable material contain 9 percent kaolin on average. Although kaolinite normally occurs throughout the weathering profile (Gideon, 2005) the abundance of kaolinite is not typical of nickel-cobalt laterites, which normally give rise to magnesia-rich, alumina-poor smectites in at least small quantities. Smectite clays were not reported by PMET or by Gideon. Kaolinite, by contrast, does not usually form by weathering of ultramafic rocks, which have very low alumina contents (see Gleeson, et al., 2003, and articles in Evans, et al., eds., 1979). It is possible that the kaolinite at Nkamouna arose from weathering of the adjacent Proterozoic schists, and was laterally transported so as to become admixed with typical ultramafic-laterite minerals. The kaolinite does not contain cobalt and does not appear likely to influence mining or metallurgical processes.

Other Minerals

Serpentinites and other ultramafic rocks typically have very low aluminum content. At Nkamouna and Mada the weathering of aluminum-bearing minerals in the schists - principally micas and feldspars - gave rise to mobile aluminum ions which migrated laterally and vertically and precipitated to form gibbsite, $\text{Al}(\text{OH})_3$. Gibbsite is locally abundant at Nkamouna but also occurs in many ultramafic-derived laterites worldwide. Gibbsite composes on average < 1 percent of the bulk mineralogy at Nkamouna (PMET, 2002).

Comparison with Other Deposits

While Nkamouna is clearly a laterite deposit formed by in-situ weathering of ultramafic rock, several features distinguish Nkamouna from most of the known wet-tropical nickel laterites.

From the earliest exploration stages it was recognized that Nkamouna displayed an unusual laterite stratigraphy, mainly with regard to the presence of abundant ferricrete breccia within the laterite sequence. In most laterites worldwide, ferricrete, if present, occurs at the surface or beneath a surficial ferricrete breccia ("canga"). At Nkamouna, the ferricrete is well-developed, and is sandwiched between the Upper Laterite and the Ferralite. It is not clear whether the Upper Laterite is forming by dissolution of the Ferricrete, or whether the Ferricrete is forming at the expense of the overlying Upper Laterite.

The data in Table 9-3 indicate that Nkamouna is highly atypical in its low Ni:Co ratio. Nkamouna is valued mainly for its cobalt and only the high-cobalt portions of the weathering profile are included in the defined resource. Due to the high Co:Ni ratio in asbolane and the unusually large size of the asbolane wad accretions that occur at Nkamouna, a significant weight percent of the bulk mineralogy is made up by the asbolane component. Stated differently, Nkamouna's Ni:Co ratio of 2.3, is far lower than that of any of the other deposits worldwide. It should be noted, however, that the other deposits in Table 9-3 are valued for nickel, with or without by-product cobalt, and the resource figures therefore refer to the high-nickel portion of the weathering profile. Because the highest cobalt values and the highest nickel values are often in a separate level of the profile, the Ni:Co ratios are not strictly comparable. For this reason, a Nkamouna Ni:Co ratio was also calculated for some of the Ferralite intervals having at least 0.5 percent Ni. This ratio (6.3 Ni:Co) is lower than that of any of the cited deposits. Since the upper portion of the Ferralite zone contains nearly 90 percent of the Nkamouna cobalt resource, it is intuitive that the lower part of the Ferralite must have a somewhat higher ratio than 6.3:1. A separate calculation for 32 intervals at Nkamouna logged as FL/SP (Ferralite-Saprolite transition) yielded a Ni:Co ratio of 8.1:1. This transition carries the highest Ni values in many nickel-laterite deposits. This also indicates that Nkamouna is systematically enriched in Co, compared to other laterite deposits.

Nkamouna is also atypical in the very low MgO content of the Ferralite, approximately 0.5 percent. Even the highly-leached limonites mined at Moa Bay, Cuba, carried over 1.5 percent MgO in the early years of that project, where nickel is recovered by high pressure leaching with sulfuric-acid.

As mentioned above in the section on Clays, Nkamouna has abundant kaolinite, a mineral not normally indigenous to nickel-cobalt laterites. The clay-mineral issues need further study.

The presence of the internal ferricrete breccia, the unusually low Ni:Co ratios, the likely presence of kaolinite, the coarse nature of the asbolane, and the low MgO content, all suggest that the Nkamouna and Mada laterites were formed by several generations of discontinuous laterization. Decipherment of the weathering history is beyond the scope of this report, but is sure to be elucidated by ongoing investigations.

TABLE 9-3
Geovic Mining Corp.
Nkamouna Project, Cameroon
Lateritic Nickel-Cobalt Deposits World-wide

DEPOSIT	COUNTRY	STATUS	BEDROCK	GEOL. TYPE+	NI/CO RATIO, ORE	PROCESS	METALS RECOV.	COMMENTS
<i>Nkamouna high-cobalt horizon</i>	<i>Cameroon</i>	<i>Feasibility</i>	<i>sheared serpentinite</i>	<i>oxide + silicate?</i>	<i>3.0</i>	<i>sulfurous acid leach</i>	<i>Co+Ni (+Mn)</i>	<i>subject of this report</i>
Nkamouna high-nickel horizon (LL)	Cameroon	Feasibility	sheared serpentinite	oxide + silicate?	est. 6 to 8	--	none planned	possible later development
Mada	Cameroon	exploration	serpentinite	oxide+=silicate	*2.0-2.4	sulfurous acid leach proposed	Co+Ni (+Mn) planned	this report
EXMIBAL	Guatemala	former producer	peridotite, serpentinitized	oxide + silicate	25	smelting to Ni-S matte	Ni	project idle
Moa Bay	Cuba	producing	peridotite, serpentinitized	oxide	10	acid leach	Ni, Co in sulfide	in production
Nicaro	Cuba	producing	sheared serpentinite	oxide + silicate	15	ammonia leach	Ni in oxide	in production
Musongati	Burundi	undevel.	peridotite, serpentinitized	oxide + silicate	30	--	Ni, Co	pre-feasibility stage
Nickel Mountain	Oregon, USA	former producer	peridotite, not serpentinitized.	silicate	80	smelting to ferronickel	Ni + Fe*	fossil deposit, mined out
Soroako	Indonesia	producing	peridotite, variably serpentinitized	silicate	20?	smelting to Ni-S matte	Ni	in production
Bonao	Dominican Rep.	producing	peridotite, sheared serpentinite	silicate	35	smelting to ferronickel	Ni + Fe*	in production
Greenvale	Qld, Australia	former producer	peridotite, serpentinitized	clay?	15	ammonia leach	Ni, Co in sulfide	mined out
Murrin-Murrin	Western Australia	producing		clay	13	high-pressure acid leach	Ni, Co	in production
Goro	New Caledonia	construction	peridotite, serpentinitized	oxide + silicate	12	high-pressure acid leach	Ni, Co	production scheduled for 2007

NOTE: Manganese is not recovered commercially at any of these operations.

+ Classification of Gleeson, et al, 2003

* The Fe recovered in ferronickel is not a paying product

Table compiled from numerous sources, including Gleeson, et al. (2003), Evans, et al (1979), Boldt (1968), and others.