9.0 MINERALIZATION

9.1 *Laterites*

Cobalt-nickel mineralization in the Geovic deposits occurs within the weathering profile overlying serpentinized ultramafic rocks. The lateritic weathering profile forms an irregular blanket averaging perhaps 20 meters thick, but the precise average is unknown as only about 13 percent of the pits penetrate to the bottom of the weathering horizon. The mineralized laterite within the profile averages perhaps 4 meter in thickness; again, no precise thickness measurement is possible because 40 percent of the pits stopped in breccia and 47 percent of the pits stopped in ferrralite. The laterite blanket lies generally parallel to the rolling topography of the Mada plateau. The top is relatively smooth on top, but the bottom is more irregular, as weathering has locally penetrated downward into fractures and shear zones in the underlying serpentinite.

Most of the economic mineralization in each deposit is in one interval, typically made up of 1 to 3 meters of ferricrete breccia, underlain by 2 to 4 meters of ferralite. The ore types are characterized geologically by their mineral content, bulk composition, and texture, as described below. The deposit's unusual concentration of the coarsely aggregated ore mineral asbolane is highly significant, as is the thick ferricrete breccia.

9.1.1 Laterite Stratigraphy

Mada and the other 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, between which lies ferricrete breccia, with mineralization concentrated at the base of the ferricrete breccia and the top of the ferralite portion of the laterite profile. The lower portion of the profile 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 Mada 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. Most of the Geovic reports refer to Nkamouna material, but perusal of logs from Mada show a similar stratigraphy.

Upper Laterite. (UL). A purplish-red, highly magnetic, powdery clay-like soil. Ubiquitous, normally 4 to 8 m thick, except where removed by erosion at the borders of 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 one or two centimeters (cm) across, to blocks larger than a meter (m) 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 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 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 to 2 m thick, and contains up to 1.5 percent cobalt where concretion-like aggregates of asbolane occur. It is hard to dig with hand tools.

Ferralite (FL). Limonitic laterite, sometimes pulverulent, mottled, with varied shades of black, yellow, brown, red. Often foliated, reflecting relict serpentinite textures. Thickness varies but averages approximately 4 m. Consistently mineralized with good metal grades near the top (e.g., up to 0.76% cobalt) where black Mn zones occur, moderate to low Co grades lower in the unit. The MgO content is very low, averaging about 0.5 percent MgO, 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 shafts and for mining.

Silcrete (SI). This highly-discontinuous unit may lie at the boundary between the Ferralite and the upper Saprolite. Silcrete is composed of subhorizontal plates of white to grey silica, intercalated with varicolored clays. Commonly has low metal contents and is very hard to dig. It is generally interpreted to mark a former water table. Silcrete is very rare at Mada, as compared to Nkamouna, having been abundant enough to log only in one meter at the bottom of Pit 345.

Saprolite zone (SP). Composed of green, sticky clay with less than 50 percent fragments of partly weathered serpentinite, grading downward into foliated, fractured serpentinite. May have silica-filled steep fractures. Relatively poor in Co, often rich in Ni. Averages 1.5 m thick. Moderate to hard digging. Saprolite typically contains less than 40 percent Fe and elevated MgO (15 to 30 percent).

TABLE 9-1
Geovic, Ltd.
Mada Project, Cameroon
Laterite Stratigraphy, Modified Slightly from the Nkamouna 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, clays	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 at Mada
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 or quartzite, may be present instead

Serpentinite (SE). Bedrock, olive green to dark green, may be fractured and fissile, with silica-filled fractures. Uniformly low metals grades except in rare cases where garnierite-like nickeliferous silicates fill fractures. Relatively hard. Magnesium grades at Mada and Nkamouna are typically greater than 35 percent and iron contents are usually less than 10 percent

Water Table. The depth to the water table was not recorded in the Mada pits. However, Mada is characterized by several swampy areas, and the water table is generally not very deep, this being the reason that only a few pits at Mada reached bedrock or even saprolite.

9.1.2 Laterite Mineralogy

The minerals of economic interest in the Nkamouna laterites are shown on Table 9-2. Although fewer formal mineralogical studies have been undertaken at Mada, comparisons of the two deposits strongly suggest that the mineralogy is very similar. 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 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 mammilary masses or vug-fillings of radiating transparent to milky white crystals several millimeters long. Of great significance is the size of asbolane agglomerates and wad that host the cobalt and almost all of the manganese.

Table 9-2 incorporates data from various Geovic reports, and from the PMET report (2002).

Asbolane

The key mineral in the Geovic deposits, which hosts the cobalt, most of the manganese, and a significant part of the nickel, is asbolane. 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, Ltd.
Mada Project, Cameroon
Selected Minerals in Laterite Profile (based on minerals known to occur in adjacent Nkamouna deposit)

Name	Mineral Type	Formula	Origin	Typical %Co	Abundance in Co-rich material	Maximum occurrence
asbolane ("wad")	hydrated oxide-hydroxide	$(Co,Ni)_{1-y}(MnO_2)_{2-x}(OH)_{2-2y+2x}.nH_2O$	weathering	10-15	6%	LB, LL
ernienickelite	hydrated oxide	$NiMn_3O_7 \cdot 3(H2O)$	weathering	low Co, high Ni	reported*, not confirmed	?
"limonite"	oxide-hydroxide	fine-grained mixtures of goethite FeO.OH, lepidocrocite FeO.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-Fe_2O_3 (ferromagnetic)	weathering	0.00X	incl in hematite	UL, UB, LB, LL
carolite, kerolite, garnierite	silicates, mineraloids	approx formulas $(Mg,Ni)SiO_3.nH_2O$	weathering (rare)	0.0X Co, high Ni	reported*, not confirmed	saprolite
nontronite	silicate clay (smectite gp.)	$Na_{0.33}(Fe,Ni)_2(Si,Al)_4O_{10}(OH)_2.nH_2O$	weathering (rare)	0.X, 0.X to X Ni	reported*, not confirmed	saprolite
montmorillonite	silicate clay (smectite gp.)	$Na_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2.nH_2O$	weathering (rare)	low	reported, not confirmed	saprolite
kaolinite	silicate clay	$Al_2Si_2O_5(OH)_4$,	weathering of adjacent schists	0	9% in bulk sample	all
gibbsite	hydroxide	$Al(OH)_3$	weathering of adjacent schists	0	1%	UL, UB, LB, LL
silica, quartz	silicate	SiO_2	weathering, remobilization	0	5%	saprolite, serpentinite
serpentine	silicate	$(Mg,Fe,Ni)_3Si_2O_5(OH)_4$	late magmatic	0.01 Co, 0.3 Ni	<1%	saprolite, serpentinite
talc	silicate	$Mg_3Si_4O_{10}(OH)_2$		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	$(Mg,Fe,Ni)_2SiO_4$	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 $(Co,Ni)_{1-y} MnO_2)_{2-x}(OH)_{2-2y+2x}.nH_2O$ 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 prior to leaching.

Clay Minerals

Kaolinite is the most abundant clay mineral at Mada and Nkamouna (see Table 3-2), according to the PMET report (2002), which shows that bulk samples of potentially processable material contain 9 percent kaolin on average. According to Lambiv (2005), kaolinite occurs throughout the weathering profile at Mada and Nkamouna. This abundance of kaolinite is not typical of nickel-cobalt laterites, which normally give rise to magnesia-rich, alumnia-poor smectites in at least small quantities. Smectite clays were not reported by PMET or by Lambiv. Kaolinite, by contrast, does not usually form by weathering of ultramafic rocks, which have very low alumnia contents (see Gleeson, et al., 2003, and articles in Evans, et al., eds., 1979). It is possible that the abundant kaolinite at Mada and Nkamouna arose from weathering of the adjacent Proterozoic schists, and was laterally transported so as to become admixed with typical ultramafic-laterite minerals. More information on the origin of the kaolinite would be interesting, although in any case 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 Mada and Nkamouna 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, $Al(OH)_3$. Gibbsite is locally abundant at Mada and Nkamouna but also occurs in many ultramafic-derived laterites worldwide. The PMET mineralogical report revealed that gibbsite composes on average less than 1 percent of the bulk mineralogy.

Comparison with Other Deposits

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

From the earliest exploration stages it was recognized that Mada and Nkamouna display 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 Mada and Nkamouna, the ferricrete is well-developed, and is sandwiched between the Upper Laterite and the Ferralite.

The data in Table 9-3 indicate that Mada is highly atypical in its low Ni:Co ratio. Mada is valued mainly for its cobalt, and only the high-cobalt portions of the weathering profile are included in the defined resource. Mada's Ni:Co ratio of 2.0-2.4 is far lower than that of any of the other deposits worldwide, and even slightly lower than Nkamouna. 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.

As mentioned above in the section on Clays, Mada has abundant kaolinite, a mineral not normally indigenous to nickel-cobalt laterites. It is not clear at this point how much kaolinite is in the Mada profile, but it is likely similar to that at Nkamouna.

The presence of the internal ferricrete breccia, the unusually low Ni:Co ratios, and the likely presence of kaolinite, all suggest that the 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, Ltd.
Nkamouna Project, Cameroon
Lateritic Nickel-Cobalt Deposits World-wide

DEPOSIT	COUNTRY	STATUS	BEDROCK	GEOL. TYPE+	NI/CO RATIO, ORE	PROCESS	METALS RECOVERED	COMMENTS
Mada	**Cameroon**	**exploration**	**serpentinite**	**oxide+= silicate**	***2.0-2.4**	sulfurous acid leach proposed	Co+Ni (+Mn) planned	**this report**
Nkamouna high-cobalt horizon	Cameroon	Pre-feasibility	sheared serpentinite	oxide + silicate	3.0	sulfurous acid leach proposed	Co+Ni (+Mn) planned	subject of previous PAH report
Nkamouna high-nickel horizon (LL)	Cameroon	feasibility	sheared serpentinite	oxide + silicate	est. 6 to 8	--	none planned	possible later development
EXMIBAL	Guatemala	former producer	peridotite, serpentinized	oxide + silicate	25	smelting to Ni-S matte	Ni	project idle
Moa Bay	Cuba	producing	peridotite, serpentinized	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, serpentinized	oxide + silicate	30	--	Ni, Co	pre-feasibility stage
Nickel Mountain	Oregon, USA	former producer	peridotite, not serpentinized.	silicate	80	smelting to ferronickel	Ni + Fe**	fossil deposit, mined out
Soroako	Indonesia	producing	peridotite, variably serpentinized	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, serpentinized	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, serpentinized	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
* ratio in the Mada resource at 0.12% Co cutoff
** 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.