Nickel laterite deposits are formed by the prolonged and pervasive weathering of Ni silicate-bearing ultramafic rocks, generally in tropical to subtropical climates. The deposits can be further classified as hydrous silicate deposits (e.g., SLN Operations, New Caledonia), clay silicate deposits (e.g., Murrin Murrin, Australia), and oxide deposits (e.g., Moa Bay, Cuba; Cawse, Australia) on the basis of the ore mineralogy. The physical and chemical nature of a nickel laterite deposit is a function of many factors, including the composition of the parent rock, the tectonic setting, climate, topography (specifically, laterite morphology), and drainage. Nickel laterite ore is extracted using both selective and bulk mining methods in open cast mining operations. The mined ore has traditionally been processed either by hydrometallurgical leaching technology (pressure acid leach or Caron processes) to produce oxides of nickel and cobalt or mixed Ni-Co sulfides for market, or by pyrometallurgical smelting to produce ferronickel granules or nickel matte. However, recent advances in high-pressure acid leaching and continued testing of atmospheric leach technology should lead to a reduction in overall operating costs and increased exploitation of Ni laterite resources in the future.

The term “laterite” has been used very loosely in the literature, both to describe specific soil horizons, including some having quite different properties, or even to define the entire weathering profile. More specifically, the term now generally refers to the iron oxide-rich, silica-poor upper soil horizon of intensely weathered regoliths found in tropical climates (Eggleton, 2001). “Nickel laterite” refers to a regolith that contains economically exploitable concentrations of nickel, but not to a specific horizon or unit. Although the profiles of most Ni laterites do have an upper ferruginous duricrust, they rarely contain economically significant enrichments of Ni. “Nickel laterite,” therefore, is used loosely and does not conform to conventional definitions; similarly, the terminology used for different parts of the profile varies widely in the literature.

In general, a “typical” Ni lateritic profile has three or four components (Fig. 3). The base of the profile, the protolith, is the parent ultramafic rock, most commonly harzburgite (orthopyroxene-rich peridotite), or other types of peridotite or dunite (e.g., Colin et al., 1990). Nickel occurs within the silicate mineral structure of magnesium-rich olivine (or its serpentinized alteration products) in these units. Olivine is not stable in...
the presence of water during chemical weathering and breaks down, leaving a residue of amorphous ferric hydroxides, with minor amorphous silicates and other phases hosting immobile elements (such as Cr). The initial stages of weathering produces saprolite, in which the unweathered rock fabric is preserved, although most of the original minerals may have been altered. The boundary between the saprolite and the bedrock—the weathering front—is extremely irregular and may be gradational; many Ni laterites are characterized by spheroidal weathering initiated along joints and fractures, resulting in blocks of fresh parent rock surrounded by altered material (known informally as boulder saprolite). As weathering proceeds, the Mg in the protolith is almost totally leached, and Si is partially removed from the profile by the ground waters. This results in the complete destruction of primary silicates and, higher in the profile, collapse and loss of primary fabric. In consequence, Fe oxides dominate in the upper saprolite and the overlying horizon. This oxide-rich part of the profile is referred to informally as limonite and the volume of the upper collapsed portion may be as little as ~15% of the original parent rock (Golightly, 1981). A dense indurated ferruginous duricrust (also referred to as cuirasse, canga, ferricrete, or lateritic residuum) may develop at the top of the profile and protect portions of the underlying laterite profile from erosion.

In the literature, and here, these profiles are commonly represented as simple columns. In three dimensions, however, the relationship between the various units can be very complex. Figure 4 is an example of Ni grade distribution in a cross section of part of the

---


<table>
<thead>
<tr>
<th>Project</th>
<th>Country</th>
<th>Ownership</th>
<th>Main ore type</th>
<th>Ni in resource</th>
<th>% Ni grade</th>
<th>Project status</th>
<th>Rated capacity (t/yr Ni)</th>
<th>Processing route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goro</td>
<td>New Caledonia</td>
<td>INCO-BRGM</td>
<td>Oxide-silicate</td>
<td>&gt;5 Mt</td>
<td>1.56</td>
<td>Feasibility study</td>
<td>68000</td>
<td>HPAL</td>
</tr>
<tr>
<td>Sorowako</td>
<td>Indonesia</td>
<td>INCO-Sumitomo-Others</td>
<td>Silicate</td>
<td>&gt;5 Mt</td>
<td>1.80</td>
<td>Producer</td>
<td></td>
<td>Matte smelting</td>
</tr>
<tr>
<td>Simalpa</td>
<td>Indonesia</td>
<td>Rio Tinto</td>
<td>Oxide</td>
<td>&gt;5 Mt</td>
<td>1.34</td>
<td>Exploration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Koniambro FeNi</td>
<td>New Caledonia</td>
<td>Falconbridge-SMSP</td>
<td>Silicate</td>
<td>3-5 Mt</td>
<td>2.58</td>
<td>Feasibility study</td>
<td>FeNi smelting</td>
<td></td>
</tr>
<tr>
<td>Sipilou</td>
<td>Cote d’Ivoire</td>
<td>Falconbridge-SODEMI</td>
<td>Oxide-silicate</td>
<td>3-5 Mt</td>
<td>1.48</td>
<td>Feasibility study</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Murrin Murrin</td>
<td>Western Australia</td>
<td>Anaconda-Glencore</td>
<td>Clay</td>
<td>3-5 Mt</td>
<td>0.99</td>
<td>Producer</td>
<td>45000</td>
<td>HPAL</td>
</tr>
<tr>
<td>Gag Island</td>
<td>Indonesia</td>
<td>BHP Billiton-Aneka Tambang</td>
<td>Oxide-silicate</td>
<td>3-5 Mt</td>
<td>1.35</td>
<td>Feasibility study</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Bahodopi</td>
<td>Indonesia</td>
<td>INCO-Sumitomo-Others</td>
<td>Silicate</td>
<td>3-5 Mt</td>
<td>1.77</td>
<td>Feasibility study</td>
<td>Matte smelting</td>
<td></td>
</tr>
<tr>
<td>SLN Operations</td>
<td>New Caledonia</td>
<td>Eramet-SLN</td>
<td>Silicate</td>
<td>3-5 Mt</td>
<td>2.40</td>
<td>Producer</td>
<td>60000</td>
<td>Smelting</td>
</tr>
<tr>
<td>Weda Bay</td>
<td>Indonesia</td>
<td>Weda Bay-Aneka Tambang</td>
<td>Oxide-silicate</td>
<td>2-3 Mt</td>
<td>1.37</td>
<td>Exploration</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Pinares de Mayari</td>
<td>Cuba</td>
<td>Cuban Government</td>
<td>Oxide</td>
<td>2-3 Mt</td>
<td>1.07</td>
<td>Exploration</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Pomalaa East</td>
<td>Indonesia</td>
<td>INCO-Sumitomo-Others</td>
<td>Silicate</td>
<td>2-3 Mt</td>
<td>1.83</td>
<td>Exploration</td>
<td>FeNi smelting and other</td>
<td></td>
</tr>
<tr>
<td>Camaguey</td>
<td>Cuba</td>
<td>BHP Billiton</td>
<td>Clay</td>
<td>2-3 Mt</td>
<td>1.30</td>
<td>Exploration</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Musongati</td>
<td>Burundi</td>
<td>Argosy</td>
<td>Oxide-silicate</td>
<td>2-3 Mt</td>
<td>1.31</td>
<td>Exploration</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Moramanga</td>
<td>Madagascar</td>
<td>Phelps Dodge</td>
<td>Oxide</td>
<td>2-3 Mt</td>
<td>1.11</td>
<td>Feasibility study</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Prony</td>
<td>New Caledonia</td>
<td>Inco (Goro Ni)</td>
<td>Oxide-silicate</td>
<td>2-3 Mt</td>
<td>1.40</td>
<td>Exploration</td>
<td>HPAL</td>
<td></td>
</tr>
<tr>
<td>Euboea-Larymna</td>
<td>Greece</td>
<td>Larco</td>
<td>Oxide</td>
<td>2-3 Mt</td>
<td>1.00</td>
<td>Producer</td>
<td>20000</td>
<td>FeNi smelting</td>
</tr>
<tr>
<td>Onca-Puma</td>
<td>Brazil</td>
<td>INCO-Canico</td>
<td>Silicate</td>
<td>1-2 Mt</td>
<td>2.20</td>
<td>Exploration</td>
<td>Smelting</td>
<td></td>
</tr>
<tr>
<td>Cerro Matozo</td>
<td>Colombia</td>
<td>BHP Billiton</td>
<td>Silicate</td>
<td>1-2 Mt</td>
<td>2.35</td>
<td>Producer</td>
<td>55000</td>
<td>FeNi smelting</td>
</tr>
<tr>
<td>Falcondo</td>
<td>Dominican Republic</td>
<td>Falconbridge</td>
<td>Silicate</td>
<td>1-2 Mt</td>
<td>1.23</td>
<td>Producer</td>
<td>34000</td>
<td>FeNi smelting</td>
</tr>
</tbody>
</table>

1 HPAL = high-pressure acid leaching.
Cerro Matoso mine, as documented by Lopez-Rendon (1986). The complexity of Ni grade distribution shown by this diagram, relative to other features such as topography, suggests that the size, morphology, and composition of the deposits is a function of many geologic and climatic variables.

Nickel laterite deposits can be broadly classified into three types based on mineralogy of principal ore-bearing phases (Brand et al., 1998; see Fig. 3).

**Hydrous silicate deposits**

In hydrous silicate deposits, the lower saprolite is the ore horizon and the ore minerals are hydrous Mg-Ni silicates. These are the highest-grade Ni laterite deposits with mean Ni grades ranging from 1.8 to 2.5%. Locally, within the saprolite, areas of intense secondary veining and box-works can be developed. These, typically, follow relic structures, fractures, and grain boundaries, and can contain neo-formed quartz and Ni-rich minerals such as the distinctive green mineral “garnierite” (see below), which can have Ni content up to 40% (e.g., Gleeson, Herrington, Durango, Velasquez, and Koll, in prep.). In these deposits, Ni has been leached from the limonite Fe oxyhydroxide phases and moves down the profile before redepositing either in hydrous silicate minerals or substituting for Mg in altered serpentine (Pelletier, 1996). Therefore, although Ni laterites are classified as residual deposits, Ni enrichment by supergene processes is important for the formation and economics of the hydrous silicate deposits. Most of the large producing Ni laterite deposits are of this type with examples found in New Caledonia, Indonesia, Philippines, Dominican Republic, and Colombia.

**Clay silicate deposits**

In these deposits, Si is only partially removed from the weathering profile by ground water. Remaining Si combines with Fe, Ni, and Al to form clay minerals such as Ni-rich nontronite in the mid to upper saprolite. Nickel-rich serpentine can also be replaced by smectite or quartz if the profile remains in contact long enough with the ground waters for the solutions to become supersaturated in these minerals. In general, the mean Ni grades in these deposits are slightly lower than in hydrous silicate deposits (1.2%; Brand et al., 1998).
Oxide deposits
In oxide deposits, also known as limonite deposits, Ni is associated with Fe oxyhydroxides, principally goethite. Some also contain abundant Mn oxides enriched in Co. Average Ni grades are commonly about 1.2%, but there are many examples of subeconomic occurrences overlying both hydrous silicate and smectite clay deposits. The Moa Bay deposit in Cuba is the best known example of an oxide deposit in commercial production.

MINERALOGY
The ore in Ni laterite deposits occurs either as silicate or oxide minerals. The ionic radius of the Ni\(^{2+}\) ion is similar to Mg\(^{2+}\), allowing Ni substitution in Mg silicate minerals. Accordingly, many of the ore minerals are hydrous silicates such as serpentine, talc, smectite, sepiolite, and chlorite, formed during low-temperature metamorphism and subsequent weathering of the parent rock (Table 2). Commonly, these minerals have variable Ni to Mg ratios. The green silicate “garnierites,” first described from New Caledonia, do not have a well-defined composition or structure and are not a recognized specific mineral species. They are poorly crystalline, with affinities to Ni-bearing talc and serpentine-structured minerals (Brindley, 1978; Brindley et al., 1979; Fig. 5). Analyses of “garnierite” veins from Cerro Matoso in Colombia showed all these minerals to be pimelite, a poorly defined Ni-rich talc, although the main ore mineral in the Cerro Matoso saprolite is Ni sepiolite (Gleeson, Herrington, Durango, Velasquez, and Koll, in prep.). In the oxide deposits, Ni is mainly associated with goethite and, to a lesser extent, Mn oxides. The possibility of Ni adsorption on the surface of goethite or other Fe and Mn oxides and oxyhydroxides has been widely discussed in the literature (e.g., Trivedi and Axe, 2001). In recent years many studies have examined the possibility that the Ni is structurally incorporated in these minerals. For example, a recent study of natural and synthetic goethite found that 75% of Ni is substituted for Fe in the goethite structure, with the remainder associated with the asbolane structure (Manceau et al., 2000).

CONTROLS ON THE GENESIS OF NICKEL LATERITES
Composition of the protolith
The protoliths for Ni laterite deposits are predominately ultramafic rocks originally containing a high proportion of forsteritic olivine with a Ni content of between 0.2 and 0.4 wt %. Some small deposits in Greece are developed from sedimentary rocks, themselves derived from ultramafic rocks. Rarely, the regolith on other rock types may be enriched in nickel. At Cawse, for example, dolerite dikes that crosscut ultramafic units have
been deeply weathered and are composed of smectites that have concentrated Ni derived from adjacent weathering ultramafic rocks (Elias et al., 1981; Stephen Denn, pers. commun., 2002).

The most common protoliths appear to be harzburgitic peridotites that have been partially or wholly serpentinized. The nature of the protolith has a fundamental control on the genesis of the deposits. In general, these rocks are mineralogically and chemically restricted in composition, and the principal minerals—olivine, serpentine, and pyroxene—are highly prone to weathering in tropical environments (Fig. 6). Only a small proportion of the primary rock is insoluble, allowing for strong residual concentration of stable secondary oxides and silicates, many of which may contain Ni. Nevertheless, neither a higher primary Ni abundance nor a more reactive mineralogy directly influences the Ni grade in the deposits. For example, Ni grades in laterite are subeconomic at Mt. Keith, Western Australia, although the protolith contains about 0.6% Ni, of which some 0.4% is hosted by sulfides (Butt and Nickel, 1981; Brand and Butt, 2001).

The type of Ni laterite deposit is only partially controlled by the lithology. Each of the three deposit classes may be developed on peridotites, but on dunite protoliths, oxide deposits predominate. The role played by serpentinization of the protolith on the formation of these deposits is fully discussed by Golightly (1981) and Pelletier (1996). Nickel laterites on unserpentinized olivine-rich rocks are not as well documented, but tend to form oxide deposits with a thin, rocky saprolitic unit (see Golightly, 1981). Partially or wholly serpentinized protoliths are much more common and generally produce a much thicker saprolite zone, but grades tend to be lower with increasing alteration. Clay silicate deposits are reported only from serpentinized peridotites; they have only recently been identified as potentially economic. Serpentinization may also contribute to poor drainage characteristics, which has significance in smectite genesis.

Nickel laterites are rare or absent on talc carbonate rocks.

Tectonic setting
Ni laterites can develop over Phanerozoic ophiolite complexes, with many deposits in Cretaceous to Miocene accreted terrains (e.g., Schellman 1989; de Oliveira et al., 1992). These complexes tend to be pervasively faulted and jointed, and also affected by tectonic uplift that enhances relief and lowers the water table, all of which increase the through-flow of water and intensity of weathering. Other, generally lower grade, deposits are found in stable Archaean and Proterozoic cratons, associated with layered mafic complexes and komatites (Butt, 1975). In both settings, the deepest zones of enrichment and the highest grades are commonly associated with steep faults and shear zones. Conversely, major thrust faults associated with the emplacement of ophiolite complexes and with stable greenstone platforms tend to form mylonitic zones of serpentine- or talc-carbonate-altered ultramafic rocks. These are less permeable and may form hydromorphic barriers that do not concentrate Ni in the regolith.

Geomorphology and topography
Topography plays an important role in the formation of Ni laterite deposits, primarily because of the relationship with structure, drainage, and the position of the water table. In areas of high relief, many deposits, and the zones of highest enrichment, are located on upper hill slopes, crests, spurs, and plateaux and/or terraces. The water table in these topographic positions is low in the profile and, coupled with mine scale structures such as faults and joints, results in the maximum rates of leaching and drainage of solutions, enhancing both residual concentration and accumulation deep in the saprolite. Such topographic situations are sites for the generally high-grade, hydrous silicate deposits formed on peridotitic rocks in Indonesia, New Caledonia, Colombia, Oregon (United States), and the Urals (Russia).

In areas of low relief, drainage is impeded and the water table is high. Such situations are common in cratonic settings and occur locally in accreted terrains. The reduced water flow slows the rates of leaching and removal of weathering solutions, so that Ni concentrations are largely residual, with little absolute accumulation except where faults have led to increased leaching. However, local restrictions and ponding behind impervious weathered dolerite dikes may give locally high grades (e.g., Elias et al., 1981). Over peridotites, high water-tables and impeded drainage result in the formation of low-grade smectite clay deposits in the saprolite (e.g., Murrin Murrin on the Yilgarn craton, Western Australia). Over dunite, impeded drainage tends to favor the formation of oxide deposits (e.g., Cawse, Western Australia) and the local accumulation of silica. Tectonic uplift plays an important role in some deposits by rejuvenating the topography and, in some locations, lowering previously high water tables, resulting in the reworking of zones of enrichment. Typically, this enhances the accumulation of high Ni grades at the base of the saprolite. Such processes are likely to have been important in New Caledonia where many of the ophiolites have multiple terraces and the deposits are commonly found in the bases of eroded plateaux (Golightly, 1981).

Climate
Climate plays an important role in the formation of Ni laterite deposits. Most are formed in savanna (e.g., New Caledonia, Cuba) or humid tropical (rainforest) climates (e.g., Colombia, Indonesia). The warm temperatures and high rainfall, combined with high biogentic activity, allows for the rapid chemical weathering necessary to form the deposits in areas of high relief where erosion rates are also high.

There are, however, many deposits in other climatic zones, including temperate (Urals, Russia; Kazakhstan), Mediterranean (Oregon, United States; Greece; Albania) and warm semi-arid (Western Australia). These deposits are probably much older, having formed under similar climates to those of the present savannas or rainforests, at various times in the late Palaeozoic, Mesozoic, and early Cenozoic. Many deposits in the Balkans and central Asia have been buried by later sediments.

**FIGURE 6.** Solubility of the common minerals in the lateritic profile at near neutral pH. The solubility of silica is independent of pH at these conditions (after Golightly, 1981).
(Glazkovsky et al., 1977; Valeton et al., 1987); they are, thus, protected from subsequent erosion. Nevertheless, minor diagenetic alteration and interaction between the ore and sediments can occur, including reduction to Ni sulfides and chamosite (Glazkovsky et al., 1977), and redistribution of Ni into chlorite because hydroxides are altered to chlorite (Albandakis, 1981). Deposits in Western Australia are preserved because of the stability, low relief, and minimal erosion of the Yilgarn craton. Some modification of the deposits has occurred due to slow, ongoing weathering under semi-arid conditions, principally manifested as silification and the precipitation of magnesite (Brand et al., 1998).

**Groundwater and organic matter**

The chemistry of waters that have interacted with Ni laterite profiles is quite distinctive. At the base of the profile, they are characterized by high concentrations of dissolved Mg and Si and relatively high pH, as shown in Figure 7 for waters from the Cerro Matoso mine in Colombia. Analyses of waters from New Caledonia and Colombia suggest that bicarbonate, rather than sulfate and chloride, is the dominant anion. This observation suggests that biogenic activity and organic compounds in these tropical soils may have a role in the development of at least the upper part of these profiles. The role of termites in disturbing the laterite profile by carrying saprolitic material to the surface has been discussed (e.g., Truckenbrodt et al., 1991). However, there have been few specific studies of the role of biogenic processes in the formation of Ni laterites. At present, many experimental and field-based studies in geomicrobiology are focused on identifying the role of biogenic processes in mediating the phase changes between amorphous Fe phases, Fe oxyhydroxides, and hydroxides. There are a small number of recent studies on the role of bacteria in the mobilization of Ni from Fe oxides (e.g., Quantin et al., 2001; Zachara et al., 2001). Numerous papers on the role of organic agents in leaching Ni laterite ores in the mineral processing literature (e.g., Alibhai et al., 1993; Sukla and Panchanadikar, 1993) suggest this may be an interesting avenue for future research.

**Rates of weathering**

The rate of formation of lateritic profiles is not well constrained. Mass balance calculations suggest weathering rates of 5 to 50 mm per 1,000 yr, with an average of 20 mm per 1,000 yr, so that a lateritic profile may develop in 1 to 6 m.y. (Nahon, 1991; Nahon and Tardy, 1992). These authors also note that basic and ultrabasic rocks weather two to three times faster than other rock types. Trescases (1975) had estimated that, in New Caledonia, the downward rate of lateritization is between 140 and 125 m in 1 m.y. in the mountains and at least an order of magnitude less in the plateaux areas, due to less efficient drainage. The more rapid weathering in mountainous areas is offset by faster rates of erosion, which may result in the destruction of deposits. Golightly (1981) suggested that between 20 and 100 m of peridotite must be leached to form saprolite ores, which can be achieved in about 1 m.y. However, rates of weathering are dependent on local processes and are likely to be highly variable from place to place.

**MINERAL PROCESSING AND EXTRACTION**

There are currently three commercial methods of processing Ni laterite ores. Because of the variability of the mineralogy in these deposits, different processing techniques are generally better suited to particular parts of the profile. However, this variability also permits some beneficiation of the ore before processing. In silicate ores, for example, less-weathered remnants of parent rock can be removed mechanically. In mixed silica-oxide deposits, in which the ore is associated with Fe and Mn oxides, barren silica can be removed by screening after crushing. Basic descriptions of nickel laterite processing technologies were reviewed by Simons (1988), although this work does not include more recent developments, such as high-pressure sulfuric acid leaching.

Most of the major Ni laterite producers are mining predominantly hydrous silicate ore for energy-intensive pyrometallurgical processing (partial reduction and smelting of dried ore). The main products are ferronickel granules and nickel matte, which are used in stainless steel production. High Ni recoveries are achieved by these operations, but Co is not recoverable as a byproduct. Many deposits have their own electrical generating plants (e.g., Cerro Matoso) because of the high-energy requirements that are arguably the single most important factor in determining the economic viability of hydrous silicate Ni laterite deposits. Access to low-cost hydroelectric power is a distinct advantage (e.g., Soroako, Indonesia).

The less common Caron process is used for treating oxide ores. This process...
involves the drying and roasting of ore in a reducing atmosphere, followed by low-pressure ammonia leaching. Both Ni and Co are recovered by solvent extraction and then further refined. Again, like smelting, ore drying and reduction roasting consume significant amounts of energy. As a result, this technology is unlikely to be chosen in the future for new nickel laterite projects.

There has been a recent resurgence in processing oxide deposits by high-pressure acid leach (HPAL) technology. Sulfuric acid at temperatures of 250°C or more and pressures of 4,500 kPa leach Ni and Co from predominantly oxide ores (Krause et al., 1998). The metals are extracted from the leach solution by precipitation as sulfides (by addition of H₂S) or as hydroxides (by addition of lime), or by solvent extraction and electrowinning. This process is also applied to clay silicate ores but the relatively high levels of Si in these deposits can cause problems at the autoclave stage and the process becomes more expensive. The dominant operating cost components of HPAL are associated with bulk supply of sulfur and the production of sulfuric acid. For many years, the only HPAL producer was Moa Bay in Cuba (operating at slightly lower pressure and temperature). Recent decreases in the cost of sulfur and improved solvent extraction and autoclave technologies have led to increased interest in this processing technology. Three new plants in Western Australia at Bulong and Murrin Murrin (smectite silicate ores) and Cawse (oxide ore) came on stream in 1999, but all have had serious capital and operating cost problems, as well as engineering and construction materials problems. A novel HPAL plant is also being planned for Goro in New Caledonia to treat both oxide and hydrous silicate portions of the profile (e.g., Mihaylov et al., 2000). Despite the difficulties that have been experienced by this new generation of HPAL plants (see Elias, 2002), economics favor this technology over the Caron leaching and the smelting technologies and it is likely that more HPAL plants will be constructed in the future to meet the growing demand for nickel as sulfides resources become depleted.

EXPLORATION

Exploration for Ni laterites does not present significant technical problems. In the past, a variety of conventional prospecting and geochemical techniques (e.g., stream sediment surveys) have found Ni laterites, and prospective ultramafic rocks commonly have distinctive soils and plant communities. However, these techniques now have little practical relevance in modern exploration. The occurrence and distribution of ultramafic rocks is now well known in most, if not all, deeply weathered terrains. They can be readily and more precisely delineated at regional to local scales by airborne magnetic surveys, which can also be used to outline lithological variation and stratigraphy, favorable structures, and intrusions that may act as impermeable hydromorphic barriers. Within appropriate areas, preliminary geomorphological, regolith-landform, and structural maps can be prepared from aerial photography, a variety of remote sensing techniques, and magnetic surveys to determine the most prospective sites for potential Ni accumulation. Airborne electromagnetic surveys may also assist in 3D regolith mapping. Follow-up by inspection, field mapping, and drilling are used to outline the potential resource. Soil geochemical surveys are inappropriate precursors to drilling, because they respond to the regolith “stratigraphy” exposed by dissection, rather than providing an indication of Ni distribution at depth. Mine-scale exploration is essential in order to delineate different ore types based on mineralogy and mineralogical assemblages rather than using Ni (and/or Co) grades alone. Properly planned exploration may differentiate ores, such as silica and/or Fe-Mn oxides, that can be physically upgraded, or may delineate varieties inappropriate for processing and that should be blended or discarded. Multi-element analysis is commonly used for the latter purpose, including attempts at calculating normative mineralogy, but there is scope for further improvements in this field to maximize the efficiency of HPAL and other processes. As noted above and illustrated in Figure 4, Ni laterite deposits show great variation in the distributions of Ni and other elements, profile thickness, and other characteristics.
over short distances. Advanced exploration for accurate estimation of resources and reserves, and for reliable mine planning, therefore, relies on having an adequate drilling density; generally a 25- to 50-m grid is used. Subsequently, precise grade control and careful blending of mined ore categories are required to minimize variation in the composition of plant feed and thus optimize plant operating conditions. Grade control commonly requires drilling on grids of 5 to 10 m.

CONCLUSIONS

Presently, most Ni production comes from sulfide deposits. In the future, the increasing cost of mining sulfide ores underground, diminishing economic sulfide resources, and increasing environmental compliance costs may have a strong impact on the economics of mining these deposits in the future. The economic viability of Ni laterite deposits is controlled not only by the nature of the resource but also by other factors such as infrastructure, location, and access to low cost energy sources. Environmental issues that need to be addressed in the development of a deposit include the rehabilitation of large open pits, disposal of tailings, and revegetation. As outlined above, improvements in mineral processing technologies may have a large impact on viability of lateritic deposits, particularly for oxide deposits. These issues, along with the large resource base, make the future of laterite mining potentially very important.

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