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# Ni-Co Laterites—A Deposit Model

By Erin Marsh and Eric Anderson

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## Introduction

Nickel-cobalt (Ni-Co) laterite deposits are an important source of nickel (Ni).  Currently, there is a decline in magmatic Ni-bearing sulfide lode deposit resources (Dalvi and others, 2004).  New efforts to develop an alternative source of Ni, particularly with improved metallurgy processes, make the Ni-Co laterites an important exploration target in anticipation of the future demand for Ni. This deposit model provides a general description of the geology and mineralogy of Ni-Co laterite deposits, and contains discussion of the influences of climate, geomorphology (relief), drainage, tectonism, structure, and protolith on the development of favorable weathering profiles. This model of Ni-Co laterite deposits represents part of the U.S. Geological Survey Mineral Resources Program's effort to update the existing models to be used for an upcoming national mineral resource assessment.

Ni-Co laterites are supergene deposits of Ni ± Co formed from the pervasive chemical and mechanical weathering of ultramafic rocks. The formation of secondary concentrations of Ni ± Co significant enough for an economic resource requires a protolith lithology that is primarily enriched in Ni.  Ultramafic rocks can contain as much as 0.3 percent Ni (Lelong and others, 1976).  These rocks occur within ophiolite complexes as harzburgite and dunite, or within komatiites and layered complexes as peridotites and dunites (Brand and others, 1998).  The extreme weathering removes all elements except the least soluble ones from the protolith.  The residual material can average as much as 5 percent Ni and 0.06  percent Co (Freysinnet and others, 2005).  Since Ni-Co laterites were first studied, scientists recognized that the enrichment of Ni in the weathering profile is controlled by several interplaying factors (as with the development of all pedoliths) which include parent rock, climate, chemistry/rates of chemical weathering, drainage, and tectonics (Norton, 1973; Lelong and others, 1976; de Vletter, 1978; Ogura, 1986; Golightly, 1981, 2010; Gleeson and others, 2003; Freysinnet and others, 2005).

Ni-Co laterites have been classified based upon their weathering profile and by their mineralogical characteristics. Wet, wet-to-dry, and dry-to-wet climate scenarios are used to classify Ni-Co laterites with regard to the weathering profile and the interplay of the factors mentioned above (Golightly, 1981, 2010).  These three regional climate scenarios help describe the variation found in Ni-Co laterite deposits (table 1). This classification focuses more on process than product, whereas the mineralogical characteristics classification relies on the products made by these processes.  This deposit model will concentrate on the mineralogical classification, because it is understood by researchers that the factors involved in the development of the weathering profile are key to the concentration of Ni and Co in particular minerals. The mineralogical characteristics subdivide the Ni-bearing ores into oxide, clay, or hydrous magnesium (Mg)-silicate types,  which have significant differences from a recovery perspective (Samama, 1986; Brand and others, 1998; Gleeson and others, 2003; Freysinnet, 2005; Golightly, 2010). All three mineralogical types of ore may be present in a single Ni-Co laterite deposit. The metalliferous laterites are mineralogically complex, discontinuous, and often have Ni enrichment in more than one of the weathering profile zones (Lelong and others, 1976). Some deposits are

subsequently mechanically weathered, re-deposited, re-concentrated, and possibly covered by new sediment (Golightly, 1981).

Ni laterites make up 72 percent of the global Ni resource and only 42 percent of the global produced Ni (Elias, 2002; Dalvi and others, 2004). This disparity stems from the expense and complexity of the metallurgy involved in extracting Ni from the mineralogically diverse and erratic Ni concentrations through a laterite profile. Three different processes are used to extract Ni and Co from the respective enriched layers; the processes include a carbon process or acid leaching for the oxide mineralization and a smelting process for the clay and hydrous Mg silicate mineralization (Elias, 2002; Dalvi and others, 2004). Recently, an ore-processing technique was developed to treat the entire laterite profile. This innovation, DNi, developed by Direct Nickel, is a hydrometallurgical process capable of extracting 95 percent of the Ni and 85 percent of the Co in laterites (Direct Nickel, 2010). With the success of the DNi hydrometallurgical process, Ni-Co laterites may be a much larger contributor to the world's production of Ni.

## History

The term laterite was first defined by Buchanan (1807). The term is derived from the Latin word (later) for brick and was used to describe the indurated clay in India, which Buchanan saw contained a large concentration of iron and hardened upon surface exposure. Buchanan's application of the term is quite specific to material used for building. Depending on the perspective of the researcher, the term laterite has been applied to a variety of aspects of tropical weathered rocks. Laterite has been known as a variably cemented sesquioxide-rich soil, a surficial or near surface reddish soil, and also by an assortment of mineralogical definitions (Helgren and Butzer, 1977; Schellmann, 1986). The term has since evolved to describe a profile in a tropically weathered regolith in which the most soluble elements are removed and the least soluble elements are progressively redistributed throughout a series of more to less weathered protoliths to form a concentrated deposit (Samama, 1986).

Weathering is the most fundamental process in the formation of Ni-Co laterite deposits. Two phases of weathering can occur in Ni laterite deposits. Initially, the protolith of the Ni laterite may be weathered to serpentinite, which is subsequently weathered into a laterite profile concentrating Ni and Co. For the latter process, many factors are involved in creating a complicated profile. Weathering depends on the mineralogical characteristics of the parent rock, the Eh and pH of the circulating water, geomorphology, and climate (Ogura, 1986). The Ni-Co laterite deposits are formed from the chemical weathering of the ultramafic rocks that removes the most soluble elements (Mg, calcium (Ca), and silicon (Si)) and concentrates the least soluble elements (iron (Fe), Ni, manganese (Mn), Co, zinc, (Zn), yttrium (Y), chromium (Cr), aluminum (Al), titanium (Ti), zirconium (Zr), and copper (Cu)) (Brand and others, 1998). Mechanical weathering of the host material by fractures and faults, increases the surface area exposed to the water driving the chemical weathering.

Ni-Co laterites can occur surficially as *in situ* deposits, buried as karst (Albania and Greece), or as linear/fault-hosted deposits (Urals) (Golightly, 1981). For this model, we will focus entirely on the *in situ* deposit types because linear and karst type deposits have similar mineralogy as the *in situ* deposits but are further complicated by their setting in fault zones or along the contacts between ultramafic carbonate rocks.

## Profile Formation and Mineralogy

Within the three mineralogical subtypes of Ni laterite deposits (oxide, clay, and hydrous Mg-silicate), there are over 30 Ni-bearing minerals that have been recognized (Brand and others, 1998;

Gleeson and others, 2003; Freysinnet, 2005; Golightly, 2010). Their distribution as ore is not universal or consistent.    Terms used to describe the progressively developed stages of weathering in a laterite profile are listed in table 2 along with their typical mineralogy.

The general mineralogy of a Ni laterite profile can be separated by paragenetic sections (fig. 1). The lower section consists of the unweathered protolith, such as fresh or primarily serpentinized dunite or peridotites. Peridotites, dunite, and primary serpentinized alterations of these rocks are the source of the Ni in these regolith supergene deposits. The major constituent of these rocks is olivine (with varying amounts of pyroxene) and alteration products that include serpentine and chlorite. Above this is a saprolite layer consisting of remnants of the protolith and lizardite, goethite, magnetite, maghemite, chromite, and hydrous Mg- and Ni-rich silicates.  At the top of the saprolite is a transition into a clay-rich layer.  Above the clays is a limonite layer with goethite, maghemite, hematite, gibbsite, and Mn-oxyhydroxides, such as lithiophorite and asbolan.  At the top of the profile is a hematite- and goethite-rich ferricrete or iron cap.

The oxide minerals are goethite, hematite, asbolan, lithiophorite, and heterogenite. Most of the Co occurs in these Mn-oxyhydroxides.  Nontronite, beidellite, montmorillonite, and saponite make up the Ni-bearing minerals of the clay-silicate type Ni laterite ore.  There are generally five groups of silicate minerals in the hydrous Mg-silicate type Ni laterite ore, which include the poorly crystalline garnierite group, sepiolite group, serpentine group, talc group, and chlorite group (Brand and others, 1998; Freyssinet and others, 2005).

## Example Deposits

It is helpful to look at specific occurrences to illustrate the development and diversity of Ni and Co in a laterite deposit.  The Nickel Mountain deposit in Riddle, Oregon is a hydrous Mg-silicate type Ni laterite, as are the deposits in New Caledonia, California, and North Carolina.  Murrin Murrin, in Western Australia, is a classic clay ore Ni-Co laterite deposit.  The Cawse deposit in Australia, as well as many of the deposits in Cuba, are oxide ore Ni-Co laterite deposits.  A few deposits in Greece and the Ural Mountains (Russia) are karstic Ni-Co laterite deposits.  The Bulong deposit in Western Australia contains both oxide and clay ores.  The Goro deposit in New Caledonia has economic Ni grades in each zone of its profile. More detailed grade and tonnage summaries of known Ni-Co laterite deposits are presented by Berger and others (2011).

### Nickel Mountain, Oregon

The Nickel Mountain deposit is located in the Klamath Mountains of Oregon.  Its setting is unique in that it lies outside of the typical 20 degrees north and south of the equator that delineates most of the other Ni-Co laterite deposits. The Nickel Mountain deposit developed from the Tertiary weathering of Jurassic peridotite, dunite, and serpentinite. The orebodies occur at the crest of the Klamath Peneplain and along the terrace below.  The top of the laterite profile has been weathered away, leaving only the saprolite layer with a thin oxide-weathered cap that developed during more recent exposure (Chace and others, 1969).   The average Ni grade was between 1.18 percent and 1.5 percent, with a total of 26.7 million tonnes (Mt) produced between 1954 and 1998, and an estimated total size of the deposit to be 63.8 Mt (Cumberlidge and Chace, 1968; D.F. Briggs, unpub. data, 2006; Eckstrand and others, 2008; U.S. Geological Survey, 2011).  Though hydrous Mg-silicate is the dominant ore at Nickel Mountian, 20 percent of the reserve is held in oxides (U.S. Geological Survey, 2011).

## Murrin Murrin, Western Australia

In 2005, the Murrin Murrin deposit contained a resource of 334 Mt and reserves of 145 Mt at 1.07 percent Ni and 0.085 percent Co (Elias, 2006). The topography of the area is generally low and subdued. The ore deposit developed from thoroughly serpentinized peridotite, a komatiitic olivine cumulate in the Late Archean Norseman-Wiluna greenstone belt (Monti and Fazakerley, 1996; Wells and Butt, 2006). The cumulate exhibits all textural variations from orthocumulate to adcumulate (Gaudin and others, 2005). This is an important feature that has an effect on the thickness and development of the weathered zones in the laterite profile. The serpentinized peridotite contains 0.2 percent Ni, mostly hosted in lizardite (Gaudin and others, 2005). Two areas of serpentinized peridotite outcrop in the Murrin Murrin area.

The laterite profile consists of five zones upward, which include: unweathered country rock at the base, saprolite, smectite, limonite (known as the ferruginous zone at Murrin Murrin), and a cap of colluvium. The developed profile is locally influenced by faulting and shearing, but most of the variation in the profile mineralogy can be directly correlated to the underlying lithology where aluminum-rich orthocumulates develop more chlorite and therefore thicker clay zones (Wells, 2006). The highest Ni concentrations occur in the clay zone. The cobalt occurs in Mn-oxides in the limonite zone and upper part of the clay zone. Unlike many other Ni-Co laterites, there is no garnierite found at Murrin Murrin, which may be due to the parent rock at Murrin Murrin being entirely serpentinized (Gaudin and others, 2005). Golightly (1981) speculated that garnierite is only present where the parent rock is fresh to partially serpentinized.

## Moa Bay, Cuba

In general, Ni-laterite deposits in northeastern Cuba are oxide-type (Gleeson and others, 2003). As with many Ni-laterite districts, there are areas of exceptions in northeastern Cuba where hydrous Mg-silicate is the main ore type (Proenza and others, 2007).

The Moa Bay district is located in northeastern Cuba. It produced 33,599 tonnes (t) of Ni and 3,721 t of Co in 2009 (Sherritt, 2010). Contained metal was reported as 0.76 Mt Ni, with a grade of 1.27 percent Ni (Freyssinet, 2005). The oxide-type deposits in Moa Bay developed from the weathering of serpentized peridotites (harzburgite), as well as dunite, of the Mayari-Baracoa ophiolite belt, which prior to laterization contained 0.2 percent Ni (Roqué-Rosell and others, 2010; de Vletter, 1955). In an environment of low relief and heavy rainfall, the olivine, clinopyroxene, and antigorite of the partially serpentized ultramafic rocks were gradually leached of their most soluble elements, Mg and Si, whereas the less-soluble components, Fe, Ni, Co, Al, and Cr, were enriched.

A weathering profile was created with economic amounts of Ni and Co, which formed in a continous process and caused the enrichment zone to progressively move along the weathering profile (de Vletter, 1955; Lelong and others 1976). At the Yagrumaje oxide-type Ni-laterite deposit in Mao Bay, the laterite profile consists of a ferricrete cap underlain by limonite containing goethite, maghemite, hematite, and gibbsite, as well as Mn-Ni-Co oxyhydoxides. The limonite is underlain by saprolite consisting of lizardite, goethite, magnetite, maghemite, chromite, and hydrous Mg-silicates. These layers overlay the protolith of serpentized peridotite and harzburgite (Roqué-Rosell and others, 2010). Because the Moa Bay district is an area of lower relief, some deposits are enriched due to the lateral transportation and subsequent re-weathering of lateritic material from higher elevation (Linchenat and Shirokova, 1964). The Mn-Ni-Co oxides occur at the base of the limonite zone as veins and coatings or concretions along fractures (de Vletter, 1955; Proenza and others, 2007). The Ni and Co occur in goethite (0.3–4.5 weight percent (wt%); 0.1–1.7wt%), maghemite (0.5–8 wt%; 1.1 wt%), and lithophorite (up to 12 wt%; 6 wt%) (Proenza, 2007).

## Secular Variation

Worldwide, Ni-Co laterite deposits occur within 20 degrees of the equator with a few exceptions, such as the hydrous Mg-silicate ore deposit in Riddle, Oreg., and deposits in the Ural Mountains. Their global distribution is a reflection on two factors: the ultramafic protolith from which they developed and the climate in which they developed. Retallack (2010) gives a complete analysis on the secular variation of Ni laterites. He describes the deposits as suffering from "the pull of recent," a concept discussed by Hay and Wood (1990) and Wilkinson and others (2009), as they are surface deposits and thus easily susceptible to denudation. Retallack (2010) notes that the initiation of laterite deposit formation was approximately 2,300 million years ago (Ma), just subsequent to the onset of the first "Great Oxidation Event" (Rye and Holland, 1998), and that older laterites (approximately 3,430 Ma; Ohmoto and others, 2007) are weathered banded iron formations. Retallack (2010) also describes the importance of $CO_2$ in the process of hydrolytic weathering and that prior to 392 Ma there was a scarcity of laterite formation because the high amount of $CO_2$ that can be produced in rain forest soils was not seen before this time (Sheldon, 2006). A combination of atmospheric $CO_2$ spikes and paleoclimatic fluctuations occurred during the development of the deposits that formed far from the equator, such as those in Oregon and the Ural Mountains.

## Exploration and Geophysics

Exploration is generally focused on finding ultramafic rocks with potential for laterite development (Golightly, 2010). Geochemical indicators for Ni-Co laterite deposits are Ni, Co, and Cr (Cornelius and others, 2001; Butt, 2004).

Modern geophysical methods used at multiple scales can be helpful during exploration for Ni-Co laterite deposits. At a regional scale, aeromagnetic, radiometric, gravity, and optical remote-sensing techniques provide insight into the broad crustal framework in which Ni-Co laterite deposits may be hosted. These methods are effective for mapping ultramafic and serpentinized rocks, as well as their weathered products. In addition, gravity and magnetic methods can be used to map fault zones. At a deposit scale, magnetic, gravity, electromagnetic, electrical, and ground-penetrating radar methods can be useful in delineating the weathering profile of the Ni-Co laterite deposits. Interpretation of these datasets is non-unique, and therefore should be constrained with independent information, such as geologic mapping or multiple geophysical techniques.

## Conclusions

The Ni-Co laterites are a supergene enrichment of Ni and Co formed from the pervasive chemical and mechanical weathering of ultramafic rocks. The laterite profile develops from the progressive weathering of ultramafic parent rocks, which occur in accretionary terranes as Alpine-type, as well as large thrust sheets, of obducted ophiolites and in cratonic areas as komatiites (Brand and others, 1998; Berger and others, 2011). These laterites occur within 20 degrees of the equator, with a few exceptions. Weathering is generally more pervasive along fractures and faults. The weathering progresses from the development of saprolite layers on the bedrock, to clay alteration of the saprolite, then to oxide alteration of the clay and hydrous Mg-silicates the limonite layer, and concludes with the hematite alteration of the oxides capping to the profile with ferricrete. The Ni can be concentrated in any of the layers, depending on the extent of the weathering process, which is effected by the climate, drainage, and tectonics of the deposit setting.

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**Figure 1.**    Idealized cross section through a Nickel laterite weathered profile illustrating all the possible layers. Natural profiles are more complex and contain diverse sequences of any or all of the layers shown. Profiles can be a few to tens of meters thick. Adapted from Samama (1986). (Mg, Magnesium)
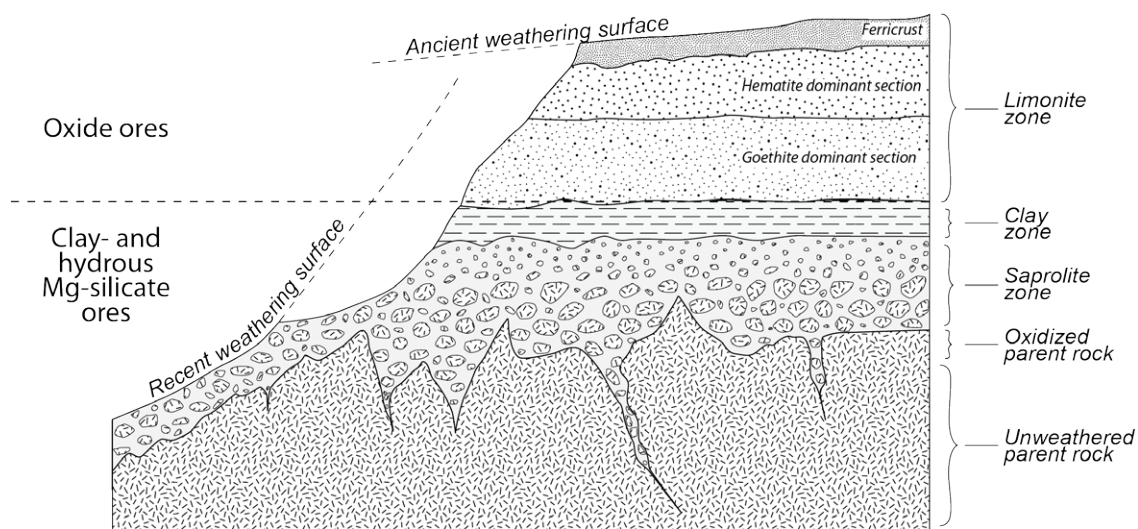
**Table 1.** Factors defining the climate scenarios used to describe the variation in Ni-Co laterite deposits. (Ni, Nickel; Co, Cobalt; Mg, Magnesium).

| Climate scenario | tectonic stablity | terrane | climate | profile development |
|---|---|---|---|---|
| Wet | active uplift | elevated | rainforest | Ni in hydrous Mg-silicates |
| Wet-to-dry | stable peneplain | flat | increasing aridity/time | Ni and Co in the oxide, clay transition zone |
| Dry-to-wet | dissected peneplain | elevated | increasing moisture/time | Ni and Co in clay and saprolite zones |

**Table 2.** Nickel laterite terminology general mineralogy. Adapted from Samama (1986) and Freysinett and others (2005).

| Ore type | Zone | Section | Alternative nomenclature | Nickel-bearing minerals |
|---|---|---|---|---|
| Oxide | Limonite | Pisolitic | nodular ironstone; ferricrete layer; durricrust; iron pan; iron cap; canga; cuirasse | Goethite Hematite Asbolan Lithophorite Heterogenite |
| | | hematite dominant | fine-grained saprolite; Red Laterite | |
| | | goethite dominant | *in-situ* limonite zone; Yellow Laterite | |
| Silicate | Clay | | intermediate zone; smectite-quartz- zone; quartz goethite zone, nontronite zone; mottle clay zone; | Nontronite Beidellite Montmorillonite Saponite |
| | Hydrous Mg-Silicate | | Saprolite; serpentine ore; soft serpentine, soft saprolite; saprolitic serpentine; coarse grained saprolite | Serpentine Group Talc Group Chlorite Group Sepiolite Group Garnierite Group |
| | Oxidized parent rock | | hard saprolite; saprolitic peridotite; saprock | |