Ni-Co Laterite Deposits of the World—Database and Grade and Tonnage Models

By Vladimir I. Berger, Donald A. Singer, James D. Bliss, and Barry C. Moring

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Introduction

Nickel is an important metal in modern metallurgy with major uses in stainless steel (about 45 percent) and nickel-based alloys (about 39 percent) (U.S. Geological Survey, 2010). Since 1950, world Ni output continued to increase almost exponentially, reaching 1.43 Mt of mined nickel production in 2009. The London Metal Exchange Ni price at the end of 2010 was more than $11 per pound. Ni consumption in the United States was 152 Kt Ni in 2009. The United States has no active nickel mines or nickel reserves.

Ni-Co laterite deposits provide one of two major natural sources of nickel and cobalt. The economic importance of this deposit type expands in direct relation with industrialization of developing countries. Until now, the world nickel supply has been predominantly from sulfide deposits. According to Gleeson and others (2003), Dalvi and others (2004), and Mudd (2010), laterites contain about 70 percent of world nickel resources, have been mined for more than 100 years, and account for about 40 percent of world nickel production.

Included in this report is a database of 120 explored N-Co laterite deposits found worldwide (appendix A). The database is a compilation of geologic and tonnage and grade data. Relevant data were collected from published and online Web sites and were found in recent issues of technical journals. The Ni-Co laterite deposits involved in our analysis are mostly well explored and are partially or entirely mined. These deposits contain reliable quantitative data on ore tonnages and Ni and Co grades.

The database, containing 66 fields, was compiled using File Maker Pro 8 software exported to Excel and tab-delineated spreadsheets. JMP 8 software was used for statistical tests and analyses. The compiled information on Ni-Co laterite deposits included the following topics: location, mineralogical subtypes, ore-processing methods related to the subtypes, development state, tonnage and grades, geological setting, morphological grouping, deposit age and distributions, and tonnage-grade models. Topic characteristics are presented and tested quantitatively. Statistical tests were performed to determine if delineated subtypes and groups of Ni-Co laterite deposits (such as mineralogical, shape, and age groups) are significantly different. Analysis of variance tests were made of differences in tonnage, mean nickel, and cobalt grades (logarithms). For this purpose, analysis of variance was used with means comparisons for each group using Student's t-test. Results of tests are expressed in tables 2, 6, and 8 and are illustrated by figures 2–4 and 7–10.

Grade and tonnage models are important in mineral-resource assessments. One purpose of this report is to update a prior Ni laterite model by Singer (1986a, 1986b). New information about known deposits, as well as data on new deposits, published during the last decades are used in the models and summaries found in this paper. The compiled database (appendix A) contains data from 120 explored Ni laterite deposits, for which a subset of 117 deposits with more confident data was included in the grade-tonnage model. In the present updated grade-tonnage model, 46 more deposits were added than were found in the previous Ni laterite model prepared by Singer (1986a, 1986b). Ni-Co laterites develop by chemical weathering of ultramafic rocks and supergene enrichment of weathering products mostly under tropical climatic conditions. Resources of most deposits are mostly in place residuum, but a few are also redeposited lateritic material. Ni-Co laterites occur along the present or paleo- surface above weathered bedrock. With respect to known classifications, three mineralogical subtypes of Ni-Co laterite deposits (Fe oxide, Mg hydrous silicate, and clay silicate) are selected by the dominant Ni-bearing mineral assemblage and statistically tested. The most economically important Ni laterite belt is confined to equatorial latitudes between 23.6 N to 23.0 S and includes almost all the youngest deposits and 72 percent of Cretaceous-Tertiary deposits.

Mineral-deposit models are important in exploration planning and quantitative resource assessments for two reasons: (1) grades and tonnages among deposit types vary significantly, and (2) deposits of different types are present in distinct geologic settings that can be identified from geologic maps (Singer and Menzie, 2010). Mineral-deposit models combine the diverse geoscience information on geology, mineral occurrences, geophysics, and geochemistry used in resource assessments and mineral exploration. Globally based deposit models allow recognition of important features and demonstrate how common various features are. Well-designed deposit models allow geologists to deduce possible presence of mineral-deposit types in a given geologic environment, and the grade and tonnage models allow economists to estimate the possible economic viability of these resources. Thus, mineral-deposit models play a pivotal role in presenting geoscience information in a useful form to policy makers. The foundation of mineral-deposit models is information about known deposits.

The latest geologic data and newly developed grade and tonnage models for Ni-Co laterite deposits in digital form are presented. Included are computer files with information about deposits from around the world. Text files allow locations of all deposits to be plotted in geographic information system (GIS) programs. The data are presented in FileMaker Pro, as well as in text files, to make the information available to a broadly based audience. The deposits are positioned on a Google Earth image, where each deposit is supplied by concise information about geographical coordinates, tonnage, and grades, and a file is provided to show locations of deposits in Google Earth. The value of this information and any derived analyses depends critically on the consistent manner of data gathering. For this reason, we first discuss the rules used in this compilation. Next, the fields of the database are explained and analyzed. Finally, we provide new a new grade and tonnage model and analysis of the information in the file.

The main contributions of this project in the Ni laterite deposit model are the following:

- Widening deposit data on Ni laterites around the world, increasing the number of deposits by 65 percent in the database, and improving confidence in the tonnage-grade model.
- The notable change in the Ni laterite grade and tonnage model since the model by Singer (1986b) is that reporting Co has expanded from 20 percent to 56 percent of all deposits in the data set. This expansion allowed the addition of the 50th percentile for Co grades in the present model.
- Statistical investigations of mineralogical subtypes, age groups, and shape-size groups of deposits resulted in proper testing of quantitative characteristics to provide additional tools for resource assessments.

Rule Used

A mineral deposit is a mineral occurrence of sufficient size and grade that might, under the most favorable circumstances, be considered to have economic potential (Cox and others, 1986). Deposits sharing a wide variety and large number of attributes are characterized as a "type," and a model representing that type can be developed.

Ni-Co laterite deposits are tabular bodies consisting of a weathered mantle of ultramafic massifs. Serpentinized ultramafics are commonly present and probably are supergene. Defining the sample to be used is an important consideration during data-gathering efforts. Grade and tonnage data are available at various levels of aggregation for districts, deposits, and mines. The following rule was used to determine which ore bodies were combined: data for all mineralized rock or lateritic rock within two (2) kilometers were combined. The effect of this rule is the exclusion of three of the 120 deposits in the database from the tonnage and grade models: (1) Taganito/Adlay in the Philippines consists of two closely located ore bodies that were explored by different companies (2) The Murrin Murrin deposit in Western Australia combined data two sites, South and North, separated by a distance of 9 km, (3) The Onça-Puma Project in Brazil combined data two deposits, Onça and Puma, located 16 km apart. Tonnage-grade data were listed under "Comments" in these cases.

Data Fields (Characteristics and Preliminary Analysis)

Information on the explored Ni-Co laterite deposits included in the database and grade and tonnage models is contained in the files Ni-Co Laterite DB.fp8, Ni Laterite DB.xls, and Ni Laterite DB.txt, which are FileMaker Pro 7, Excel, and tab-delineated text files, respectively. The fields in the files are described and preliminarily analysis is given below. The "n.d." abbreviation in various fields indicates "no data," "not detected," or "not defined."

Deposit Name

The most recent deposit name is used in the "NameDeposit" field. There is another field, "OtherNames," which contains alternative names that have been used for the deposit. A third field, "Includes," provides the names of deposits and sites that have been combined with the primary deposit as a result of the two-kilometer minimum separation rule.

Table 1. Country names and country codes used in this report.

Country	State, Province	Country Code
Albania		ALBN
Australia	Queensland	AUQL
Australia	South Australia	AUSA
Australia	West Australia	AUWA
Brazil		BRZL
Burundi		BRND
Cameroon		CMRN
Colombia		CLBA
Côte d'Ivoire (Ivory Coast)		IVCO
Cuba		CUBA
Dominican Republic		DMRP
Ethiopia		ETHP
Greece		GREC
Guatemala		GUAT
India		INDA
Indonesia		INDS
Kazakhstan		KAZN
Kosovo (Serbia)		KSOV
Macedonia		MACA
Madagascar		MDGS
Myanmar (Burma)		MYAR
New Caledonia		NCAL
Papua New Guinea		PPNG
Philippines		PLPN
Puerto Rico		PTRC
Russia		RUSA
Serbia		SRBA
Solomon Islands		SLMN
Turkey		TRKY
United States	Oregon	USOR
Venezuela		VNZL

Locations

A number of fields are provided to show the deposit's location. "Country" and "StateProvince" are used for general locations. "CountryCode" is an abbreviated version of the country information (table 1). Degrees, minutes, and seconds of longitude and latitude are provided in separate fields. Decimal degrees of latitude ("LatitudeDecimal") and longitude ("LongitudeDecimal") are calculated from the degrees, minutes, and seconds fields. Southern latitudes and western longitudes are negative values.

Longitudes and latitudes of all localities were checked visually and corrected using Google Earth 5.1.Deposits included in the database and tonnage and grade models are located on the world map (fig. 1) and are plotted on the Google Earth 5.1 image using the Ni Laterite.kmz file. The deposit symbols are divided by color into three age groups. The detailed description of the age groups of Ni laterite deposits is in the Weathering Age section of this report. In addition to map figure 1, we have included a file (of2011-1058.kmz) that plots the locations of the deposits in Google Earth and a shapefile folder (in of2011-1058_shapefile.zip) to allow ease of mapmaking.

Mineralogical Subtypes of Ni-Co Laterite Deposits

According to common mineralogical classifications (Freyssinet and others, 2005; Gleeson and others, 2003), three Ni-Co laterite deposit subtypes are recognized as (I) clay silicate, (II) Mg hydrous silicate, and (III) Fe oxide. Brand and others (1998) pointed out that these mineralogical subtypes usually are confined to different layers of the same profile and that most laterite deposits contain both silicate and oxide Ni laterites. Detailed consideration of special fields of "Laterite Profile" and "Mineralogy" has confirmed the three subtypes are mixed in a majority of Ni laterite deposits. Deposits of a "pure" end-member subtype found in this database are rare and the deposit classification used depends on dominant nickel-bearing mineral assemblages in the laterite profile.

Table 2. Tonnage and grades of mineralogical subtypes of Ni laterite deposits. [Significant differences at the one percent level or less are indicated in bold. Tonnage reported in millions of metric tonnes (Mt); the column designed "Tonne" gives the sum of tonnes of all deposits given within each category]

Subtype of Ni-Co laterite deposits	Number of deposits	Total ore tonnage			Median Ni grade, %	Median Co grade, %
		Tonne	%	Median		
I. Clay silicate	12	879	7	25	1.27	0.06
II. Mg hydrous silicate	44	4,077	32	47	**1.44**	**0.06**
III. Fe oxide	61	7,629	61	66	**1.14**	**0.09**
	117 (total)	12,585	100	56	1.3	0.08

Short definitions of nickeliferous subtypes are placed in the "Type" field, including number indicators of the determined subtype. The major mineralogical subtype is commonly associated with some subordinate subtype named in parentheses. Quantitative characteristics of the three subtypes, including median values of tonnage and nickel and cobalt grades, are shown in table 2. Frequency of nickel-bearing minerals and other minerals of the nickeliferous laterites are displayed in tables 3 and 4.

Although original descriptions of the profiles are mostly schematic, the integrated lateritic sequence consists of the follows units (from top to bottom): (1) overburden, moved or formed in place, (2) duricrust, including ferricrust, silcrete, and calcrete; ferruginous laterite, often named 'limonite zone' (3) argillaceous saprolite; coarse saprolite; and weathered ultramafic source rock. The nickel-bearing minerals listed in table 3 are grouped according to their composition and laterite subtype. Minerals of the serpentine group, talc, and chlorite are dispersed and ubiquitous.

Given the compilation (table 2) is representative of all Ni-Co laterites, the most important and widely distributed subtype, Fe-oxide, composes 61 percent of the world Ni laterite tonnage, or more than 7,600 Mt. The Mg hydrous silicate subtype contains 32 percent of the world tonnage or 4,100 Mt. The clay silicate subtype includes 12 deposits that have small tonnages compared to the two common subtypes named above.

While the clay silicate subtype is rare as a pure end-member, clay minerals are abundant and widespread in nearly all parts of laterite profiles. A seemingly distinct classification is affected by the mixed mineralogy of real laterite profiles. The median tonnages appear to be different among the three subtypes (fig. 2), but statistical tests show that the values are not significantly different.

Meanwhile the assumption that nickel and cobalt grades in the two main subtypes are the same was rejected (figs. 3 and 4). Higher nickel grades in Mg hydrous silicates likely are due to the positive associate of Ni with Mg in subtype II. Higher Co grades in subtype III may be due to the association of Co with Mn oxide.

Activity

Characteristics of the activity at the deposits are described in four fields containing a name of the company or companies in the “OwnerOperator” field. Where the discovery date is known, it is recorded in the “DiscoveryDate” field. The startup date of mining is listed in the “StartUp” field. The current state of deposits (exploration, feasibility study, development, and mining) is noted in the “Status” field. The “Status” field is used to record the exploration and development situation of the property, including theproduction condition, if appropriate. The “Status” field allows an estimation of general current economic conditions production condition, if appropriate. The “Status” field allows an estimation of general current economic conditions in the nickel laterite industry. Among 120 known deposits included in the database, development and mining operationsare reported at 44 deposits, 34 deposits are in exploration, 19 deposits underwent past exploration and are mostly abandoned or idle, 20 deposits are past producers, and eight deposits mined out. Given these observation are representative, 67 percent of Ni laterite deposits are part of a current activity of one type or another. This may suggest a forthcoming increase of laterite nickel-cobalt production, however, Ni-Co production can be hampered by unforeseen, unfavorable market conditions and by implementation of environment-protection actions.

Table 3. Frequency of main non-nickeliferous minerals of Ni-Co laterites. [Count, number of deposits; %, percentage of deposits containing the mineral.]

Minerals	**Count**	**%**
Clay silicates		
smectite and illite	92	77
nontronite	88	73
gibbsite	72	60
clay minerals (not differentiated)	20	17
kaolinite	8	7
montmorillonite	5	4
saponite		
Mg (Ni) hydrous silicates and associated Mg (Ni) minerals of talc-serpentine group		
serpentine	77	64
garnierite	40	33
talc	38	32
kerolite	19	16
pimelite	16	13
nepouite	13	11
lizardite	11	9
antigorite	10	8
sepiolite	9	8
pecoraite	8	7
willemseite	6	5
falcondoite	2	2
Fe and Mn oxides		
goethite	92	77
limonite	88	73
hematite and maghemite	72	60
Mn-oxide (including cryptomelane, pyrolusite, ramsdelite)	20	17
todorokite and chalcophanite	8	7
lithiophorite	5	4

Table 4. Frequency of main non-nickeliferous minerals of Ni-Co laterites.[Count, number of deposits; %, percentage of deposits containing the mineral.]

Minerals	Count	%
chromite and Cr-spinel	70	58
magnetite	65	54
quartz	78	65
chalcedony	21	18
opal	19	16
tridymite	2	2
magnesite	21	18
siderite	11	9
dolomite	8	7
calcite	7	6

Grades and Tonnages

Data gathered for each deposit include the average grade of each metal or mineral commodity of possible economic interest and the associated tonnage based on the total production, reserves, and resources at the lowest available cutoff grade. Each of these categories are characterized by a separate set of fields, including "standard" codes of estimated reserves and resources, such as JORC (Australia), NI 43-101 (Canada), and "A, B, and C categories" of the former Soviet classification. Additionally, reserves are defined as proven, probable, possible, and historic; resources are determined as measured, indicated and inferred, and potential and historic. The final set contains total tonnage-grade data are used in the models' creation. All tonnages reported here ("Tonnage") are in millions of metric tons (Mt) and tonnes. In some sources, reported tonnages are defined as "wet" or "dry" ore (noted in "Comments"), but most data contain only tonnage values without giving this ore characteristic. Nickel and cobalt grades are reported in percentages. Unlike ubiquitous data on tonnages and nickel grades, cobalt grades are reported only in 67 deposits, so cobalt grades that are not available are treated as zero. The "Comments" field contains supplementary information about available Au and PGE grades. Three significant digits are used for tonnage and grades. The special field of "Source TonnGrade" indicates sources of tonnage-grade data that corresponds to "References". If required, details about reserves, resources, and production is placed in "Comments." In some deposits, the resources are outlined only by drilled sites nested within a wider nickeliferous laterite areas and open on the flanks.

Ore Processing

Different processing methods applied to Ni laterite ores are divided in three groups: pyrometallurgical (ore smelting), hydromellurgical (ore leaching), and a Caron process that combines pyro- and hydro- processes (Speriadi, 2005; Wedderburn, 2009,2010). Hydrometallurgical processing includes atmospheric leaching (for example, direct nickel, chloride, and sulfation) and HPAL (high pressure and temperature acid leach). All these groups are generalized in the database to four fields, NiFe Smelt, Atm Leach, HPAL, and Caron, defined on the alternative basis as 'yes' or 'no' (the last one presented by empty space). In compilation of metallurgical features, we used data not only on mined deposits but also on explored deposits in the process of being developed for production. These fields are accompanied by a "Recovery Ni%" field. The data, in spite of their incomplete character, allow approximate estimation of the role of ore processing methods on mineralogical subtypes. Table 5 shows numbers of the actual or proposed ore processing method after metallurgical testing.

Table 5. Mineralogical subtypes of Ni laterite deposits and ore-processing methods.

Subtype of Ni-Co laterite deposits	Number of deposits	Number of processing records	Ore-processing methods			
			NiFe smelt	HPAL	Atm Leach	Caron
I. Clay silicate	12	8	5	1	2	-
II. Mg hydrous silicate	44	35	26	7	2	-
III. Fe oxide	61	47	9	21	7	10
Total	117	90	40	29	11	10

The scant reporting on subtype I, clay silicate, raises concerns about how representative the data are on processing. Better reporting on subtypes II and III may assure that these data are more likely representative. Among processing methods applied to deposits of subtype II, Mg hydrous silicate, smelting is prevailing, with 74 percent of the reporting deposits processed in this manner. Ores of subtype III, Fe-oxide, are processed mostly by the advanced HPAL method (45 percent), as well as by three other traditional methods: Caron (21 percent), smelting (19 percent) and atmospheric leaching (15 percent). In some deposits, such as Jacaré, Brazil, and Koniambo, North Caledonia, oxide and silicate ores are processed by different methods, hydrometallurgical and pyrometallugical, respectively.

Shape and Size of Ni Laterite Deposits

A number of fields are used to record the deposit's shape and size. Besides source data, these categories were defined and measured through detailed study of the Google Earth 5.1 images, where it was possible to identify and measure actual deposit sites.

In order to capture information consistently about the size ("DepositArea") and shape of Ni-Co laterites, as presented in two-dimensional projection to the surface, the shortest dimension is measured as the distance between parallel lines that just touch the object ("DepositWidth"). After the short dimension is determined, the long axis is measured perpendicular to it using the same criteria ("DepositLength"). Where published estimates of the projected area of the body are not available we estimated the area using the standard formula for an ellipse area ($S=3.14159\ LW/4$), where S is area in km^2, L is length, and W is width, in kilometers (km), of the measured site. Thickness (m) of the Ni-Co laterite ore body is recorded in the "DepositThick" field that is a part of the total laterite mantle thickness ("LateriteThick").

Bivariate statistical analysis (fig. 5) shows the positive correlation between deposit area and tonnage, with the correlation coefficient $r=0.56$ significant at the 1-percent level.

The linear fit on the plot matches the equation (with rounded numbers): $y=1.29+0.5x$, where y is in $\log_{10}$ Mt, and x is in $\log_{10}$ km^2. The equation may have a practical application to prospective Ni-Co laterite regionalassessments. Statistical tests show no significant correlations between deposit tonnages and deposit or laterite thicknesses.

Meanwhile, there is a positive correlation between $\log_{10}$ total laterite thickness and thickness of a nickeliferous layer at thedeposit, with a correlation coefficient of $r=0.77$ which is significant at the 1-percent level (fig. 6). The linear fit on the plot matches the equation (with rounded numbers): $y=0.0 +0.82x$, where y is the $\log_{10}$ deposit thickness, and x is the $\log_{10}$ total laterite thickness. This equation also may be applied to Ni-Co laterite regional assessments.

The “DepositShape” field contains a short description of the configuration and geomorphology of Ni-Co laterite occurrences either as a single laterite blanket, or as a group of sites combined in one deposit. According to original deposit characteristics and remote image analyses, three generalized types were recognized: plateau Ni-Co laterite, hill Ni-Co laterite, and linear Ni-Co laterite. These types are indicated in three respective fields: “plateau”, “hill”, and “linear “, each witha ‘yes’ or ‘no’ option (the latter represents empty space). The shape fields are added with two detailed fields: “low relief”, and “karst”, typical of only a few linear deposits.

Plateau type (n=40) indicates a laterite blanket covering a considerably flat, wide extensive area, elevated above adjacent lands and dissected by ravines in some deposits.

Table 6. Tonnage and grades of Ni laterite deposits of different shape types. [Significant differences at the 1-percent level or less are indicated in bold. * L, length, and W, width, of the Ni-Co laterite deposit area. ** Tonnage reported in millions of metric tons. *** Explanation in the text.]

Shape type of Ni-Colaterite deposits	Number of deposits	Median area, sq. km	Median ratio L/W*	Ore tonnage**		Median grade Ni %	Median grade Co %
				Tonne	Median		
Plateau Ni-Co laterite	40	14.9	2	5,484	**71**	1.27	0.08
Hill Ni-Co laterite	65	8.2	2.5	6,001	**40**	1.3	0.08
Linear Ni-Co laterite	11	4.2	***	1,057	46	1.07	0.06
Not defined	1	-	-	43	-	-	-
	117 (total)			12,585 (total)	56	1.3	0.08

Hill type (n=65) represents remnants of partially eroded plateau laterite mantles preserved at planar top, summit, terrace, and gentle slope areas, including downslope lateritic material, as described by Golightly (1979). Linear type (n=11) indicates morphological elements, such as a long gentle ridge or flat valley extending along strike of ultramafic bodies and fault zones. Low relief (n=9) and Karst (n=4) features are further details of the smaller group of linear type deposits and are related to the higher erosion along linear controlling structures.

Quantitative characteristics of the three main Ni laterite shape types are tabulated (table 6). The only variable found to be significantly different was mean values of tonnage of the two main types, Plateau and Hill (fig. 7).

The substantially larger median tonnage of the Plateau type versus the Hill type probably correlates with the larger median area of the Plateau-type deposits and is simply another expression of the positive correlation between deposit tonnages and areas outlined above. The median area of the Hill type is notably smaller due to more extensive erosion. Statistically, the difference between areas of the two major morphological types is not significant. This also is true for the median nickel and cobalt grades. Although linear Ni-Co laterites also are defined in table 6, their number is likely too few to compare with other surface shape types. The Linear type contains only deposits of the two older groups, among them Mesozoic deposits of the Urals and southern Europe which are highly eroded, the variables about them may not be representative of younger deposits.

Geologic Setting

The geologic setting of the deposits is characterized in several data fields: tectonic setting, source bedrock and other bedrock, deposit shape and size of area occupied, laterite profile, and nickel-bearing and other minerals.

Tectonic Setting

The Tectonic Setting field contains information about age, regional name, and conventional tectonic type of the Ni-Co laterite-bearing tectonic zone. An age of such zone encompasses the entire geological scale from Archean in cratons until Cenozoic in modern island arcs. Four tectonic settings are defined in the database (with number of contained deposits in parentheses): ophiolite terranes of fold belts and magmatic arcs (n=70), ultramafic fragments (blocks and sheets) of oceanic plates obducted onto continental terranes (n=30), greenstone belts of cratons (n=8), and single-layered mafic-ultramafic and alkaline-ultramafic complexes (n=5).

Source Bedrock

Rocks below and around the Ni-Co laterite deposits are recorded here using the same terms as those used in the published maps and reports. We have used two fields in an attempt to provide some specific information. The field SourceBedrock is used for rocks that are only represented in the deposit itself and are covered by nickeliferous laterite, so they might be considered as a source of nickel and cobalt concentrations. This field includes those listed magmatic rocks associated with laterites. Table 7 shows the frequency of these rocks in the deposits. Serpentinite and serpentinized ultramafic rocks are present in the majority of deposits (87 percent), dunite (65 percent) and harzburgite (53 percent), along with widespread peridotite (46 percent), are the main source rocks. The nickel and cobalt content of unaltered and serpentinized source rocks is 0.2–0.3 wt. percent and 0.01–0.02 wt. percent, respectively. Notably higher nickel and cobalt concentrations are found in bedrock associated only with three deposits: Kastoria, Greece, 0.3–0.4 wt. percent Ni; Loma di Hierro, Venezuela, 0.3–0.4 wt. percent Ni; and Riddle, United States, 0.29–0.52 wt. percent Ni.

Other Bedrock

Country rocks that are present both in the deposits and on a regional map are placed in the field OtherBedrock, which also contains the geologic age of the rocks (in parentheses after rock definitions). In table 5, the country rocks can be divided into several categories with respect to their setting. Chromitite pods, gabbro, and norite are common (>50 percent) components of the source mafic-ultramafic complexes. The next essential group consists of basalt, diabase, ophiolitic mélange, and chert (total 66 percent), corresponding to ophiolite zones of different ages that host many Ni laterite deposits. Ophiolites mostly are accompanied by metamorphic rocks (70 percent) of prevailing Precambrian ages, and also by clastic (33 percent) and carbonate (20 percent) sedimentary rocks. The presence of limestone and other carbonate rocks may lead to laterite accumulations in karst. However, karst topography development is not necessarily limited to carbonate rocks and can develop in peridotite rocks (Golightly, 2010) and, perhaps, other rock types under extreme weathering conditions.

Table 7. Frequency of source bedrock associated with laterites and other bedrock. [Count, number of deposits; %, percentage of deposits with associated rock type. Many deposits are associated with more than one rock type. In addition, there are one or two instances of carbonatite, syenite, websterite, wehrlite, and ijolite in the database rock fields.]

Source Bedrock	**Count**	**%**
serpentinite, serpentinized ultramafics	102	87
dunite	77	64
harzburgite	62	53
lherzolite	17	15
peridotite	55	46
pyroxenite	24	21
Other Bedrock		
metamorphic rocks (gneiss, marble, quartzite, schist)	70	60
gabbro, gabbro-norite, norite	66	56
basalt (including metabasalt, diabase)	47	40
clastic sedimentary rocks (conglomerate, sandstone, shale, siltstone)	39	33
carbonate sedimentary rocks (dolomitic limestone, limestone)	23	20
intrusive rocks (granite, granodiorite, plagiogranite, diorite, tonalite)	24	21
chert	19	16
chromitite	19	16
ophiolite, ophiolitic melange	12	10

Weathering Age

Nickel-cobalt laterite deposit development requires three main features: presence of ultramafic rocks; peneplain topography; and humid, tropical climates. Laterization is a chemical and physical weathering process leading to the dissolution and mobilization of many soluble elements at the surface (Golightly, 1981; Elias, 2002; Freyssinet and others, 2005). The laterization process results in the loss of a number of elements and the concentration of other elements to sufficient grades that might be considered as economic for extraction. Gleeson (2005) has named five general epochs of laterite formation from the Carboniferous to the Pliocene. Direct age determinations of Ni laterites, such as radiometric, palynological, and paleomagnetic, are very rare and may not be exact. For example, an age of the known Murrin Murrin deposit in Western Australia was defined widely by paleomagnetic dating as Mesozoic and Tertiary (Wells, 2003). Determinations of weathering ages shown in the database were taken from publications related to the deposits. Such determinations are made mostly based on observed local geological and geomorphological relations. Using these relations, time periods of the laterite-forming weathering processes, and hence, approximate ages of Ni-Co laterite deposits were grouped into three age groups, designated as 'a, b, c' for use in the Age Group field (table 8, figs. 8–10).

Table 8. Tonnage and grades of the three age groups of Ni laterite deposits. [Significant differences at the one percent level or less are indicated in bold. Tonnage reported in millions of metric tonnes.]

Age Group of Ni-Co laterite deposits	Number of deposits	Total ore tonnage			Ni median grade, %	Co median grade, %
		Tonne	%	Median		
'a' Miocene to present	52	6,894	55	**87.5**	**1.3**	**0.072**
'b' Cretaceous to Early-Mid Tertiary	43	4,171	33	47.3	1.3	0.08
'c' Mesozoic	22	1,520	12	**42**	**1.11**	**0.06**
	117 (total)	12,585 (total)	100	56	1.3	0.08

Determinations of weathering ages shown in the database were taken from publications related to the deposits. Such determinations are mostly based on observed local geological and geomorphological relations. Using these relations, time periods of the laterite-forming weathering processes and hence Ni-laterite deposits approximate ages were grouped into three age groups, designated as 'a, b, c' for use in a field designated as Age Group (table 8, figs. 8–10).

The '**a**' group of **'Miocene to present'** consists of deposits with ages reported as being post-Oligocene, Miocene-Pliocene, Miocene-Quaternary, Miocene-Holocene, Miocene to present, Pliocene to present, and Late Tertiary to present. This group of 52 deposits is 44 percent of all deposits in the data set, and it cumulatively contains 6,894 Mt of Ni-Co mineralization, or 55percent of all Ni-Co mineralization used in the analysis.

The '**b**' group of **'Cretaceous to Early-Mid Tertiary'** ages includes deposits with ages reported as being Cretaceous-Cenozoic, Late Cretaceous-Tertiary, Late Cretaceous-Oligocene, Early Tertiary, Tertiary, late Eocene-Oligocene, and late Eocene. These 43 deposits are 37 percent of the data set and cumulatively contain 4,170 Mt of Ni mineralization and 33 percent of all mineralization found in the data set. These Ni-Co laterites can be partially or completely overlapped by Quaternary alluvium and moved debris.

Table 9. Geographical distribution of Ni-Co laterite deposits by latitude.

Latitude interval (decimal)	Number of deposits		Total ore tonnage		Number of deposits by age group					
					a, Miocene to present		b, Cretaceous to Mid Tertiary		c, Mesozoic	
	Count	%	Tonne	Median tonne	Count	%	Count	%	Count	%
59.7 N–38.5 N	23	20	1,583	43	1	2	-	-	22	100
23.6 N–23.0 S	87	74	9,998	60	51	98	36	84	-	-
24.7 S–33.6 S	7	6	1,004	140	-	-	7	16	-	-
	117 (total)	100	12,585 (total)	56	52	100	43	100	22	100

The ‘**c**’ group of ‘**Mesozoic**’ age deposits includes deposits that are designated as being Early Mesozoic, Mesozoic, pre-Jurassic (Triassic?), Triassic-Jurassic, Late Triassic-Early Jurassic, Jurassic-Early Cretaceous, Early Cretaceous, and pre-Tertiary. Even Late Paleozoic laterites were presumed to be in some of the Urals Ni-Co laterite deposits (Mikhailov, 2004). The group is made up of 22 deposits, or 19 percent of all deposits in the data set. There total content of Ni-Co mineralization is 1,520 Mt, or 12 percent of all Ni-Co mineralization. The group is distinctive because it is capped by Late Cretaceous and Eocene carbonate and clastic sedimentary rocks; some deposits exhibit low-grade metamorphism, are slightly deformed, and may be redeposited in paleokarsts. Millerite, pyrite, and pyrrhotite, along with phlogopite and rhodochrosite, may be present in some deposits of this group and probably are products of low-grade metamorphism.

The age of each successive group of Ni-Co laterite deposits corresponds to a decline in the number of deposits reported, size, and nickel and cobalt grades. This steady trend is confirmed statistically. A significant difference exists among quantitative characteristics of groups ‘a’ and ‘c.’ The ‘b’ group appears transitional between the two extremes (see table 8).The clear decrease of deposit size and nickel-cobalt grades with increasing deposit age likely is due to increased erosion and natural leaching of the older deposits. The deposits of the ‘c’ group can be considered to represent remnants of much larger Ni laterite population isolated on older paleosurfaces.

Ni laterite deposits of different age groups are confined to three latitudinal belts (table 9; fig. 1). The northern belt extends between 59.7 N and 38.5 N latitude consisting only of older Ni laterite deposits of the ‘c’ group, mainly located in two regions of southern Europe and the Urals. The Miocene Riddle deposit (42.96 N, Klamath mountains, Oregon, United States) is the only ‘a’ group deposit that falls into the belt.

The most economically important equatorial belt includes all younger deposits of the ‘a’ group (besides the Riddle) and 72 percent of ‘b’ group deposits, confined to latitude interval 23.6 N– 23.0 S. Gleeson and others (2003, p.1) pointed out that “many recently formed, and actively forming deposits are situated in equatorial latitudes” found between 20ºN and 20ºS. The southern belt (24.7 S–33.6 S) includes the eight remaining deposits of the ‘b’ group (Cretaceous to Early-Mid Tertiary) present in Australia and South America.

Worldwide belts like these might be important guides in developing tracts for use in either global or regional assessments of Ni laterites.

Spatially Related Deposits

What other deposit types are within 10 km ("Assoc Deposits less 10km") of each Ni-Co laterite deposit? In many situations, these spatially relateddeposits merely are occurrences and not economic mineral deposits. Nevertheless, many of these occurrences can be typed, and their types might provide important information about the possible association with Ni laterite deposits. Each deposit type is coded with the deposit type number and deposit type as listed in U.S. Geological Survey Bulletins 1693 (Cox and Singer, 1986) and 2004 (Bliss, 1992). Within 10 km, 31 other Ni laterite deposits are recognized. In addition, there are 21 podiform Cr deposits noted which appear to be closely associated with the same ultramafic source rocks from which the Ni laterite deposits in this study were formed. Besides listed deposit types, six Au-quartz vein deposits and one Cu-Zn VMS deposit are found within 10 km.

Preliminary Analysis—Grade and Tonnage Model

Grade and tonnage models of mineral deposits are useful in quantitative resource assessments and exploration planning. Having some idea of the possible values of alternative kinds of deposits that might be sought is critical to good exploration planning. In quantitative resource assessments these models play two roles: first, grade and tonnage models can help classify the known deposits in a region into types and therefore aid in delineation of areas permissive for types; second, the models provide information about the potential value of undiscovered deposits in the assessment area and are key to economic analyses of these resources. Construction of grade and tonnage models involves multiple steps; the first is the identification of a group of thoroughly explored deposits that are believed to belong to the mineral deposit type being modeled. Thoroughly explored here means completely drilled in three dimensions. However, some Ni laterite deposits involved in the tonnage-grade models remain open on flanks. After deposits are identified, data from each are compiled. These data consist of average grades of each metal or mineral commodity of possible economic interest and tonnages based on the total production, reserves, and resources at the lowest available cutoff grade. Here we use the deposits that have tonnages recorded in the Total Tonnage field and the associated average grades.

Many grade and tonnage models are presented in a graphical format to make it easy to compare deposit types and to display the data. The grade and tonnage plots show the cumulative proportion of deposits versus the tonnage or grade of the deposits. Individual symbols represent the deposits, and intercepts for the 90th, 50th, and 10th percentiles are plotted. Percentiles of grades that contain unreported values, such as Co, were based on the observed distributions. Co grades in Ni-Co laterite deposits were not of economic interest until recent years, so the unreported Co grades should not necessarily be considered to be lower than the Co grades reported here. The reported Co grades might be a reasonable model of the unreported grades in this deposit type.Frequency distributions of the tonnages and the nickel and cobalt grades for the deposits of the thoroughly explored deposits reported in the file can be used as models of the grades and tonnages of undiscovered deposits. The frequencies for the total tonnage and average Ni and Co grades for the general Ni laterite grade and tonnage model are plotted in figures 11–13 and are summarized in table 10. Based on the Shapiro-Wilk W test, tonnages of these deposits are significantly different from lognormal at the 1-percent level. Average Ni grades are not significantly different from lognormal distributions at the 1-percent level, but Co average grades are significantly. The significant difference for Co grades is due solely to one deposit with a very low reported grade. One notable change in the Ni laterite grade and tonnage model since the one published by Singer (1986b) is that Co grade reporting has expanded from 20 percent to 56 percent of all deposits in the data set. The larger number of deposits in the present model allowed the addition of the 50th percentile for Co grades due to the increased number of reported Co grades.

Relations among variables are important for simulations of resources, for their effect on our understanding of how deposits form, and for their effect on our assumptions about resource availability. Deposit grades are not significantly correlated with tonnages or with each other.

If there were no differences in grades or tonnages among deposit types, we could use one tonnage-grade model for all types. For this reason, it is desirable to perform some tests to determine if the types are significantly different with respect to grade or tonnages. Analysis of variance tests of differences in mean (in logarithms) tonnage and nickel and cobalt grades showed no significant differences for the subtypes or the types in the type index of Ni laterite deposits. However, the same tests performed on the lateritic Ni deposits by age groups showed that tonnages were significantly different at the 4-percent level, nickel grades were significantly different at the 1-percent level, and cobalt grades were significantly different at the 1-percent level (figs. 8, 9, and 10). The tonnages are progressively lower, and the nickel and cobalt grades are lower as the ages of the deposits become older. The age effect is largely displayed in the oldest, Mesozoic group, which mostly is located in two regions, so in most cases, no age adjustment seems justified for assessments outside of these regions. In most cases, it is recommended that the general grade and tonnage model (table 10) be used.

Table 10. Grade and tonnage models of laterite nickel deposits. [Tonnage is reported in millions of metric tons. Nickel and cobalt are reported in percent.]

		Number ofdeposits	10th percentileof deposits	50th percentileof deposits	90th percentileof deposits
General Ni-Co laterite	Tonnes	117	290	56	9.0
	Ni grade, %	117	1.8	1.3	0.83
	Co grade, %	117	0.11	0.04	0.00

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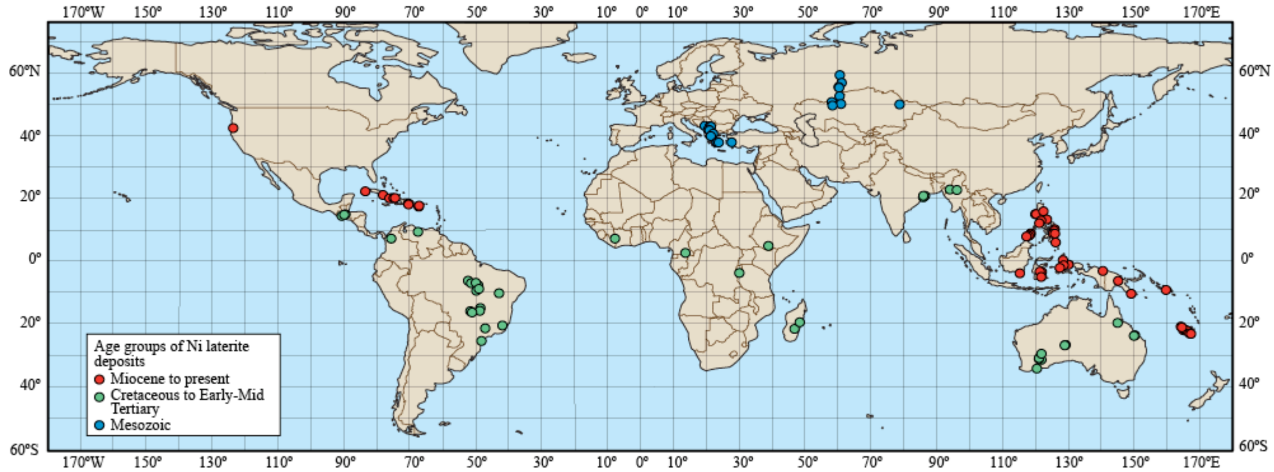

Figure 1. World map of explored Ni-Co laterite deposits of different age groups included in the database and grade and tonnage model.

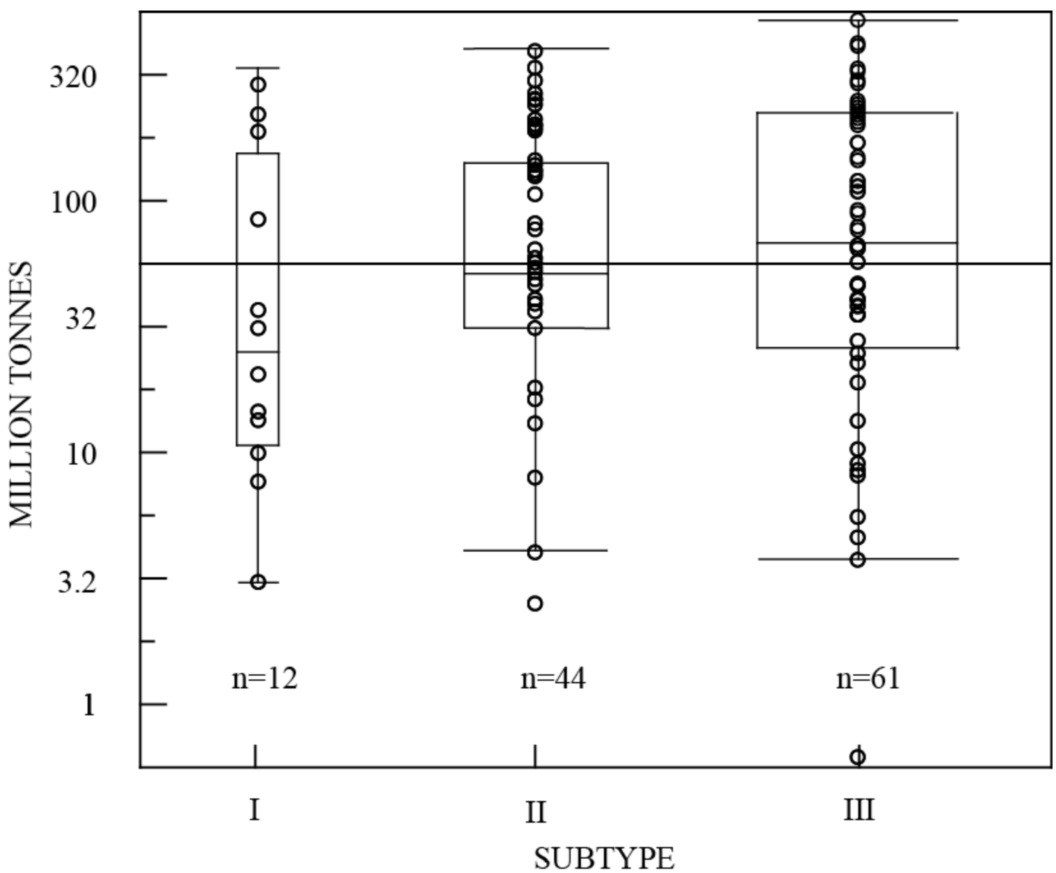

Figure 2. Box plot of deposit tonnages by nickel-cobalt laterite mineralogical subtype: I, clay silicate; II, Mg hydrous silicate; III, Fe oxide. Dots are individual deposit tonnages, median value is the centerline of box, 25th and 75th quartiles are top and bottom of box, and the line across the plot is the grand mean.

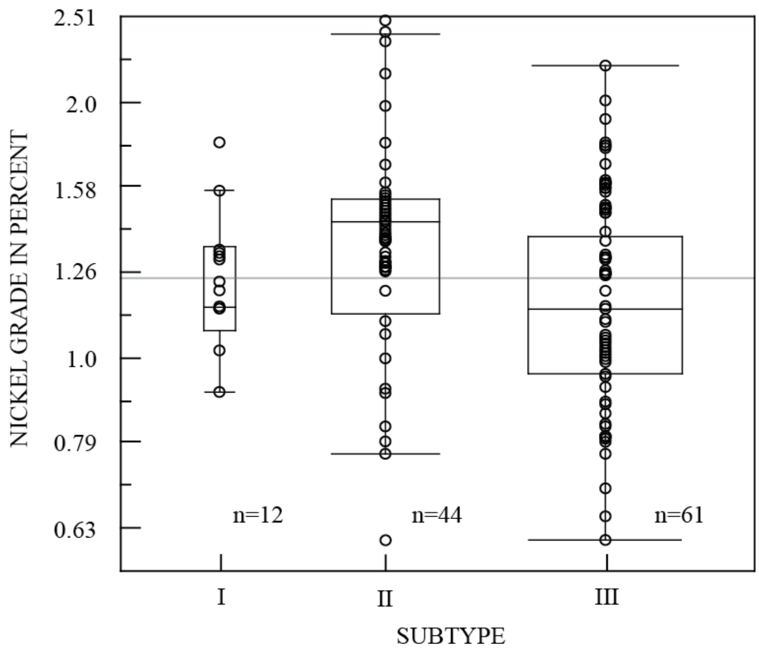

Figure 3. Box plot of average nickel grades of deposits by mineralogical subtype: I, clay silicate; II, Mg hydrous silicate; III, Fe oxide. Dots are individual deposit average nickel grades, median value is the centerline of box, 25th and 75th quartiles are top and bottom of box, and the line across the plot is the grand mean

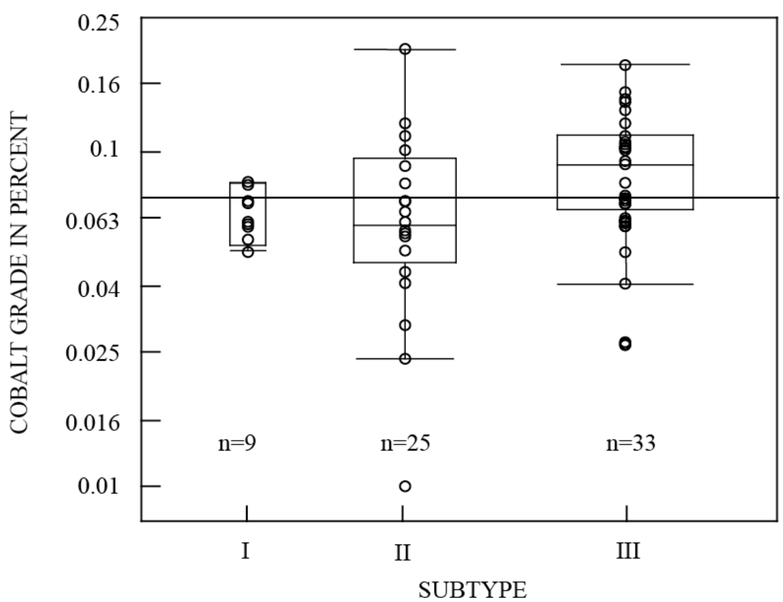

Figure 4. Box plot of average cobalt grades of deposits by mineralogical subtype: I, clay silicate; II, Mg hydrous silicate; III, Fe oxide. Dots are individual deposit average cobalt grades, median value is the centerline of box, 25th and 75th quartiles are top and bottom of box, and the line across the plot is the grand mean.

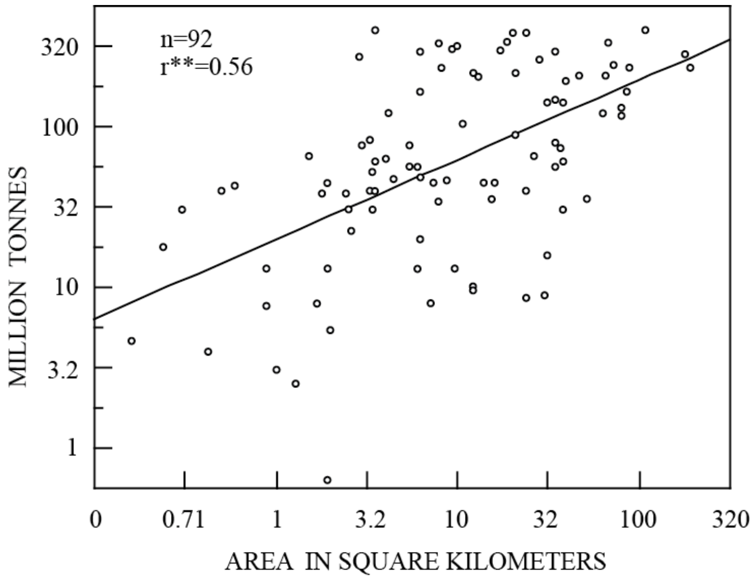

Figure 5. Bivariate plot of deposit tonnages (Mt) by area (km2) of Ni-Co laterite deposits. Dots are individual deposit tonnage and areas. The line is the linear fit matching the equation: y =1.29+0.50x, where x is the area in log base 10 km2 and y is the deposit size in log base 10 deposit size in million tonnes. Correlation between deposit area and tonnage is positive, the correlation coefficient r=0.56 is significant at the one percent level.

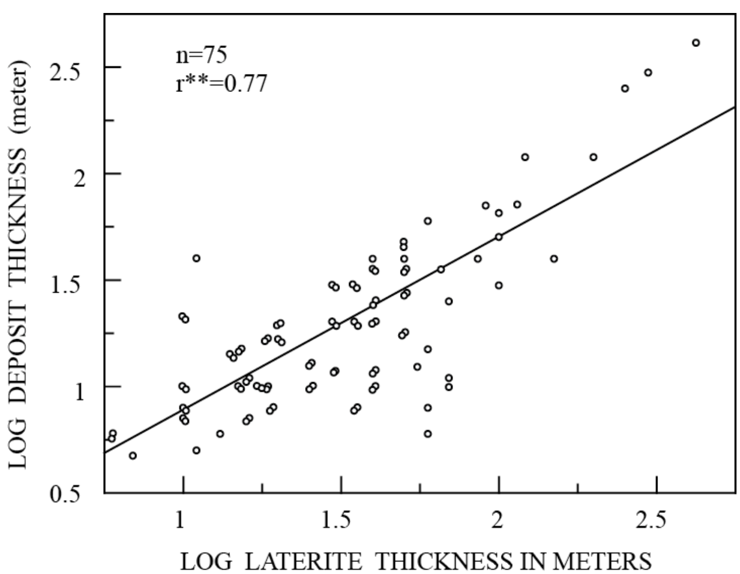

Figure 6. Bivariate plot of log deposit thickness by log laterite thickness (m). Dots are individual deposit thicknesses, the line is the linear fit matching the equation y=0.075+0.81x. The correlation between log10 laterite thickness and deposit thickness is positive, the correlation coefficient r=0.77 is significant at the one percent level.

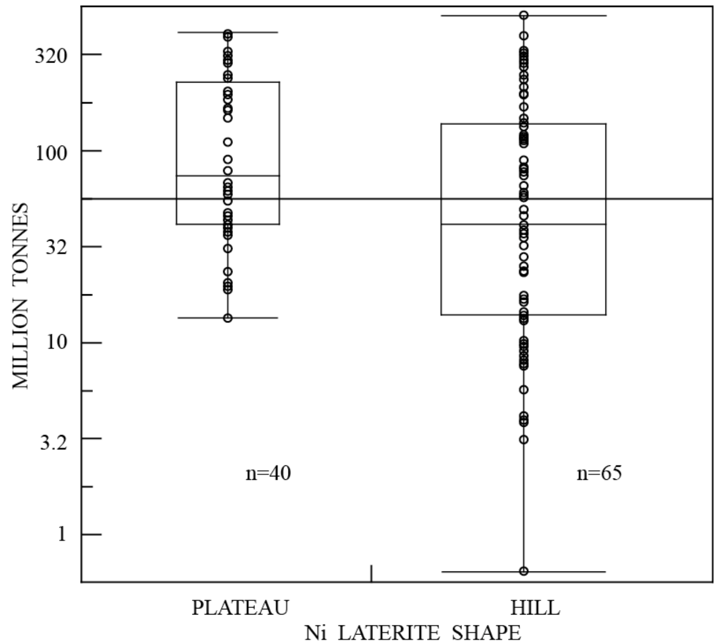

Figure 7. Box plot of deposit tonnages by shape groups of plateau and hill. Dots are individual deposit ore tonnes, median value is the centerline of box, 25th and 75th quartiles are the top and bottom of the box, and the line across the plot is the grand mean.

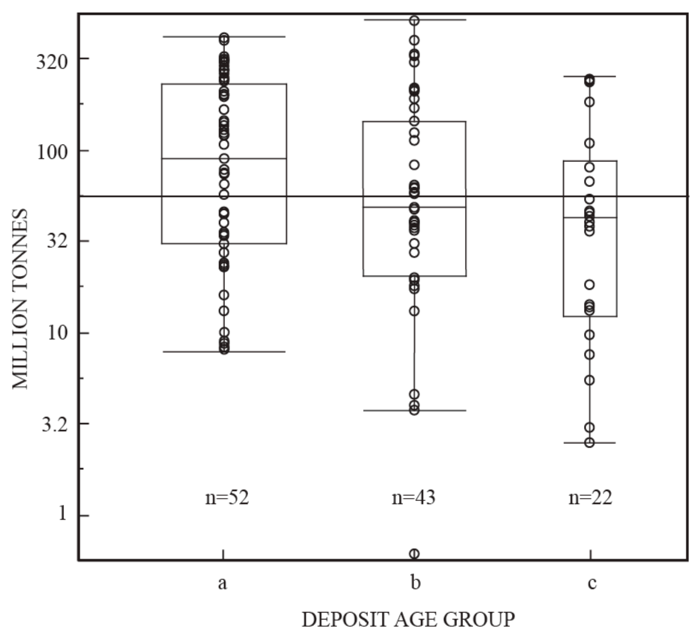

Figure 8. Box plot of deposit tonnages by age group. a, Miocene to present; b, Cretaceous to Early-Mid Tertiary; c, Mesozoic. Dots are individual deposit tonnages; median value is the centerline of the box; 25th and 75th quartiles are the top and bottom of the box; the line across the plot is the grand mean.

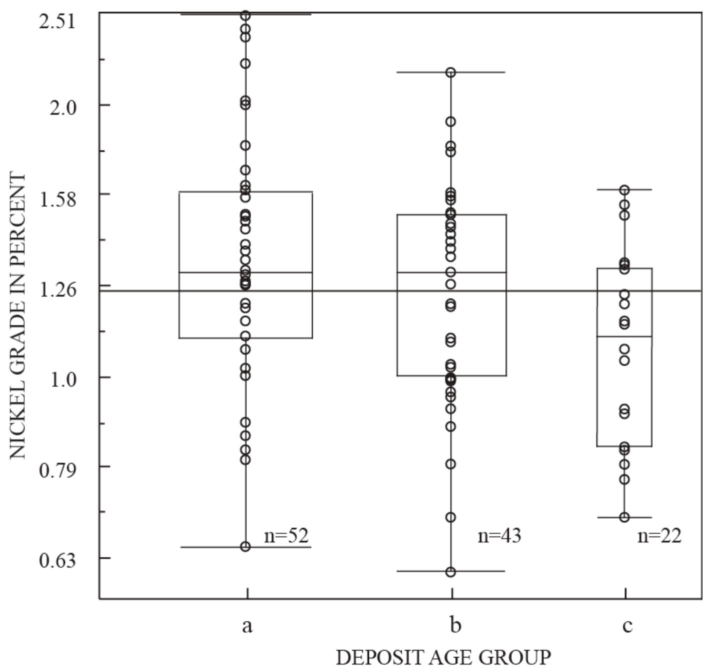

Figure 9. Cumulative frequency of ore tonnages by age group. Each circle represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the observed distribution are provided.

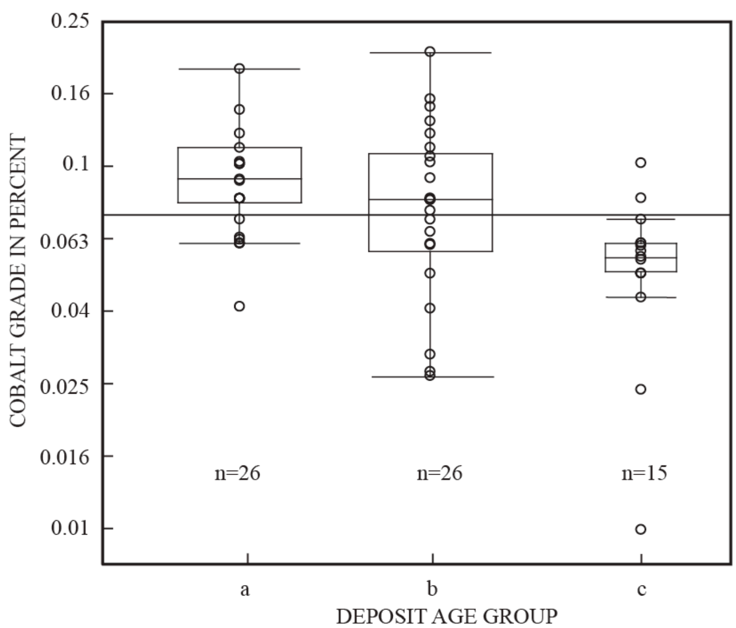

Figure 10. Box plot of average nickel grades by age group. a, Miocene to present; b, Cretaceous to Early-Mid Tertiary; c, Mesozoic. Dots are individual deposit average nickel grades; median value is the centerline of the box; 25th and 75th quartiles are the top and bottom of the box; the line across the plot is the grand mean.

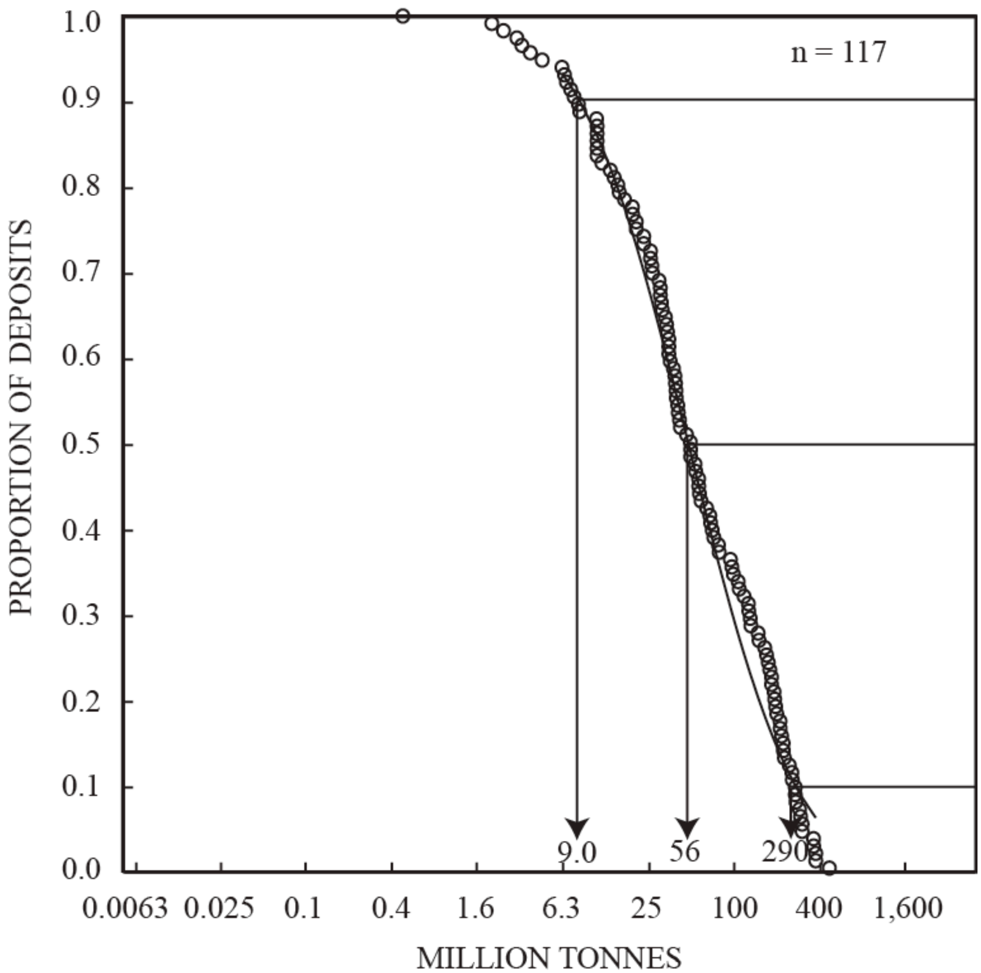

Figure 11. Cumulative frequency of ore tonnages of Ni-Co laterite deposits. Each circle represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the observed distribution are provided.

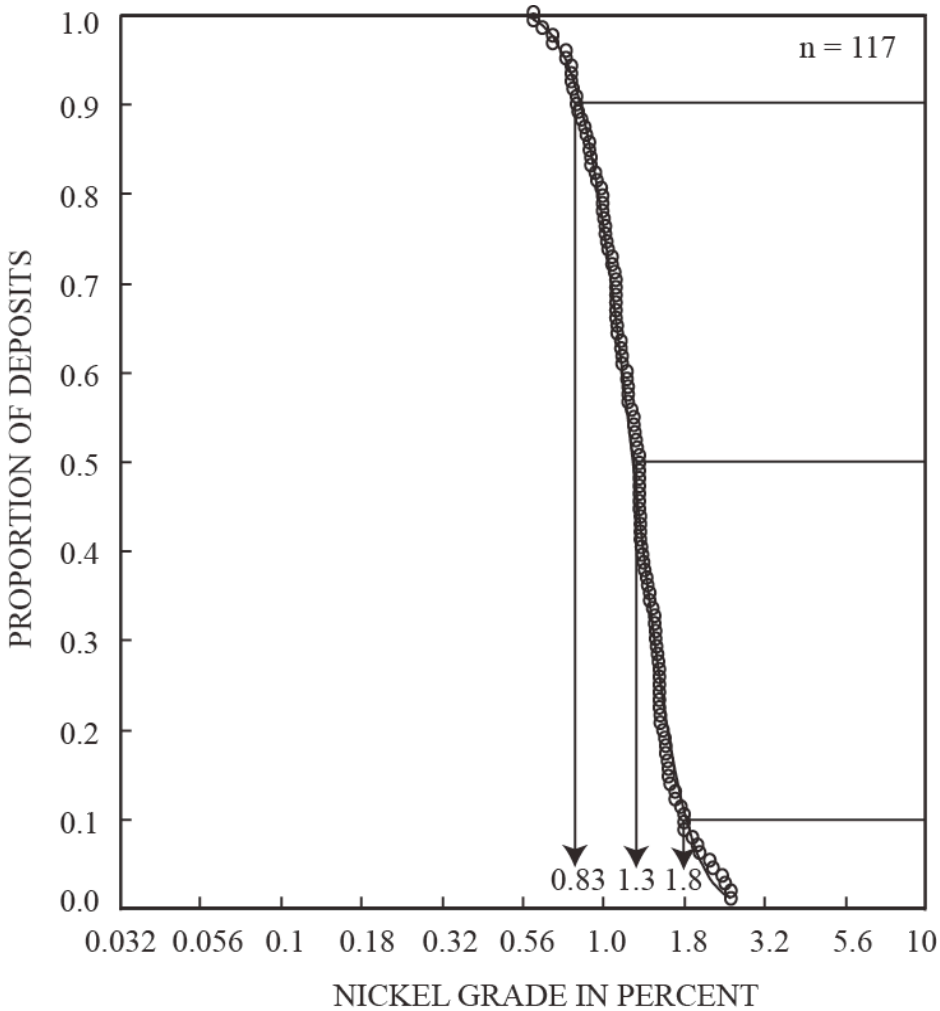

Figure 12. Cumulative frequency of nickel grades of Ni-Co laterite deposits. Each circle represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the observed distribution are provided.

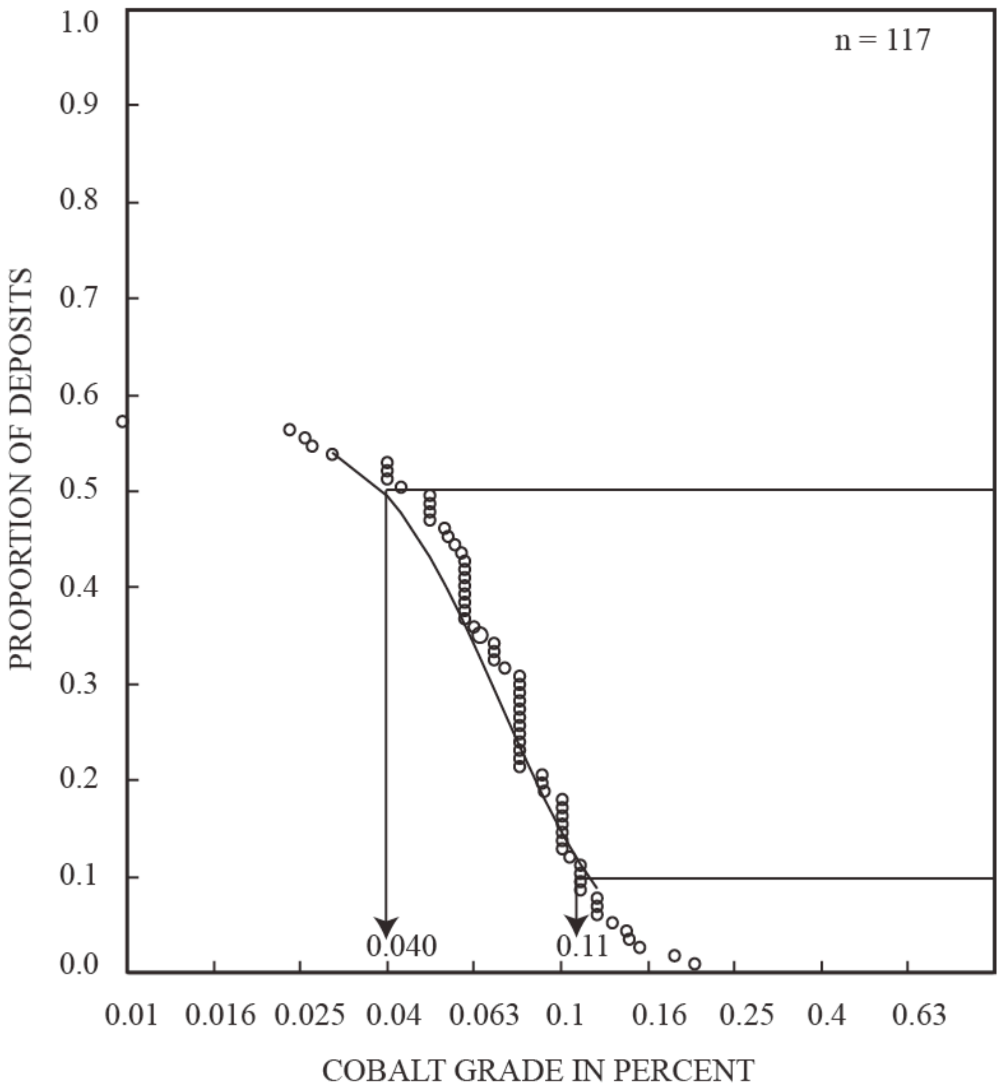

Figure 13. Cumulative frequency of cobalt grades of Ni-Co laterite deposits. Each circle represents an individual deposit. Intercepts for the 50th and 10th percentiles of the observed distribution are provided.

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Appendix A

Database files included in Appendix A of this publication consist of:

- FileMaker 7 — of2011-1058_data.fp7
- Excel — of2011-1058_data.xls
- Tab-delineated text — of2011-1058_data.txt

Map files also included in this publication consist of:

- Google Earth files — of2011-1058.kmz
- Shapefiles — of2011-1058_shapefile.zip
- Metadata — of2011-1058_metadata.txt