The Distributions and Relationships of Grade and Tonnage Among Some Nickel Deposits

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GEOLOGICAL SURVEY PROFESSIONAL PAPER 1160

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By M. P. FOOSE, W. D. MENZIE, D. A. SINGER *and* J. T. HANLEY

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An analysis of the relationships of
grade and tonnage among
several types of nickel deposits

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON:1980

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, ***Secretary***

GEOLOGICAL SURVEY

H. William Menard, ***Director***

Library of Congress Catalog-card No. 80-600140

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

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CONVERSION FACTORS

Metric unit	Inch-Pound equivalent	
Length		
millimeter (mm)	= 0.03937	inch (in)
meter (m)	= 3.28	feet (ft)
kilometer (km)	= .62	mile (mi)
Area		
square meter (m^2)	= 10.76	square feet (ft^2)
square kilometer (km^2)	= .386	square mile (mi^2)
hectare (ha)	= 2.47	acres
Volume		
cubic centimeter (cm^3)	= 0.061	cubic inch (in^3)
liter (L)	= 61.03	cubic inches
cubic meter (m^3)	= 35.31	cubic feet (ft^3)
cubic meter	= .00081	acre-foot (acre-ft)
cubic hectometer (hm^3)	=810.7	acre-feet
liter	= 2.113	pints (pt)
liter	= 1.06	quarts (qt)
liter	= .26	gallon (gal)
cubic meter	= .00026	million gallons (Mgal or 10^6 gal)
cubic meter	= 6.290	barrels (bbl) (1 bbl=42 gal)
Weight		
gram (g)	= 0.035	ounce, avoirdupois (oz avdp)
gram	= .0022	pound, avoirdupois (lb avdp)
metric tons (t)	= 1.102	tons, short (2,000 lb)
metric tons	= 0.9842	ton, long (2,240 lb)
Specific combinations		
kilogram per square centimeter (kg/cm^2)	= 0.96	atmosphere (atm)
kilogram per square centimeter	= .98	bar (0.9869 atm)
cubic meter per second (m^3/s)	= 35.3	cubic feet per second (ft^3/s)
Specific combinations—Continued		
liter per second (L/s)	= .0353	cubic foot per second
cubic meter per second per square kilometer [(m^3/s)/km^2]	= 91.47	cubic feet per second per square mile [(ft^3/s)/mi^2]
meter per day (m/d)	= 3.28	feet per day (hydraulic conductivity) (ft/d)
meter per kilometer (m/km)	= 5.28	feet per mile (ft/mi)
kilometer per hour (km/h)	= .9113	foot per second (ft/s)
meter per second (m/s)	= 3.28	feet per second
meter squared per day (m^2/d)	= 10.764	feet squared per day (ft^2/d) (transmissivity)
cubic meter per second (m^3/s)	= 22.826	million gallons per day (Mgal/d)
cubic meter per minute (m^3/min)	=264.2	gallons per minute (gal/min)
liter per second (L/s)	= 15.85	gallons per minute
liter per second per meter [(L/s)/m]	= 4.83	gallons per minute per foot [(gal/min)/ft]
kilometer per hour (km/h)	= .62	mile per hour (mi/h)
meter per second (m/s)	= 2.237	miles per hour
gram per cubic centimeter (g/cm^3)	= 62.43	pounds per cubic foot (lb/ft^3)
gram per square centimeter (g/cm^2)	= 2.048	pounds per square foot (lb/ft^2)
gram per square centimeter	= .0142	pound per square inch (lb/in^2)
Temperature		
degree Celsius (°C)	= 1.8	degrees Fahrenheit (°F)
degrees Celsius (temperature)	=[(1.8×°C)+32]	degrees Fahrenheit

THE DISTRIBUTIONS AND RELATIONSHIPS OF GRADE AND TONNAGE AMONG SOME NICKEL DEPOSITS

By M. P. FOOSE, W. D. MENZIE, D. A. SINGER, and J. T. HANLEY

ABSTRACT

Frequency distributions and relationships of tonnage and average grade among three types of nickel deposits were investigated as models for regional resource assessment: sulfide deposits associated with komatiitic rocks, sulfide deposits associated with small intrusions of diverse types, and laterite deposits. In laterite deposits, the geologic factors that influence deposit tonnage are mostly distinct from those that control deposit grade; no correlation of deposit tonnage and grade should be expected. However, in sulfide deposits, the geologic factors that influence grade and tonnage are too complex to suggest the type of relationship between tonnage and grade.

Both tonnage and grade of sulfide deposits associated with komatiitic rocks follow lognormal distributions. These deposits have a median nickel grade of 1.24 percent and a median tonnage of 9.49×10^6 metric tons. Deposit grade and tonnage have a significant inverse correlation. Analysis of komatiitic deposits from four regions revealed significant differences in grade and tonnage between regions.

The tonnage and grade of a second type of sulfide deposit, which is associated with small orogenic intrusions, were also found to be lognormally distributed. The median nickel grade of these deposits is 0.60 percent, and their median tonnage is 1.27×10^6 metric tons; these variables are statistically independent.

The tonnage, but not the grade, of laterite deposits follows a lognormal distribution. However, when the effect introduced by including high-grade silicate laterite ores was eliminated, both tonnage and grade of deposits composed primarily of oxide ore were found to follow lognormal distributions; oxide deposits have a median nickel grade of 1.36 percent and a median tonnage of 45×10^6 metric tons. These variables were found to be statistically independent.

INTRODUCTION

Regional mineral-resource assessments are essential in making land-use decisions and in determining national and international availability of minerals. Although these assessments can be made by several techniques, one of the most straightforward is to use the frequency distributions and relationships of important variables among known deposits as models of how these variables will behave among undiscovered deposits. Grades and tonnages are the most important variables.

Once models of these variables have been constructed, the problem of regional resource appraisal largely becomes that of delineating favorable areas for each type of mineral deposit and estimating the number of deposits in each area. This latter task is by no means easy, but its success in part relies on having first established a basic understanding of grade and tonnage relationships and distributions. These relationships are useful for long-term analysis of resources because they provide important information on how the quantity of resources changes as average grades of deposits worked decline.

This discussion is concerned with grade and tonnage frequency distributions and relationships for certain types of nickel deposits. Nickel is found in a wide variety of ores that are formed by different geologic processes, but most deposits may be placed in one of four broad geologic classes. Most important are sulfide deposits, most of which form when nickel sulfides concentrate within mafic or ultramafic magmas. Sulfide deposits contain approximately 20 percent of the world's nickel reserves and currently supply nearly 65 percent of the nickel mined each year (Lawrence, 1974). Nickel-rich lateritic soils are a second important deposit type. Formed mainly by chemical weathering of ultramafic rocks, these nickel-bearing soils are estimated to contain 80 percent of the world's nickel reserves. A third deposit type consists of small and relatively unimportant concentrations of nickel sulfides and arsenides deposited from hydrothermal solutions. Finally, large expanses of nickel-bearing manganese nodules have been identified on the ocean floor and may represent an important source of nickel in the future.

In this study, the grade and tonnage of several subgroups of the important sulfide and laterite deposit classes are examined. First, some of the geological features of nickel deposits in general and of these specific deposit types in particular are described. Then grade and tonnage distributions within each of the chosen deposit types are presented and compared with theoretical statistical models.

ACKNOWLEDGMENTS

The assistance of Gus Goudarzi and Glen Shaffer of the U.S. Geological Survey in the initial stages of data gathering and the critical comments of N.J. Page , R. B. McCammon, and C. E. Brown, also of the U.S. Geological Survey, are gratefully acknowledged.

SULFIDE DEPOSITS

Sulfide deposits in mafic and ultramafic rocks have supplied most of the world's nickel, even though they represent less than one quarter of the world's nickel reserves. These important deposits may be divided into two broad classes (Naldrett, 1973; Naldrett and Cabri, 1976). The first class of deposits, those in stable cratonic areas, has traditionally been the largest nickel producer. However, as a result of discoveries during the last 15 years in Canada and Australia, a second class of deposits, those in settings that have been tectonically active, is assuming greater importance. Geologic features of both classes of deposits are described in the following paragraphs; however, the data needed to statistically test the grade and tonnage relationships are available only for two subgroups of deposits belonging to the second class.

DEPOSITS IN STABLE TECTONIC SETTINGS

Large, differentiated, layered igneous complexes in stable cratonic areas have long been considered ideal targets for nickel prospecting. Largely, this has been due to the numerous nickel sulfide deposits located and mined in the Sudbury intrusion in Canada. Other intrusions similar to Sudbury are the Stillwater (Montana), Bushveld (South Africa), Muskox (Canada), Skaergaard (Greenland), and Dufek (Antarctica). Although large amounts of nickel are found in some of these intrusions, all the deposits are low grade, and either the deposits are subeconomic or nickel is not the principal mineral mined. In addition, much of the nickel may be in silicate rather than sulfide minerals. For these reasons, relatively little data have been made available about these nickel occurrences.

Although the Sudbury intrusion has many similarities to other large differentiated igneous complexes, important differences exist and may indicate that it is unique. Of particular interest is the evidence concerning the origin of the intrusion that has resulted in two differing interpretations. Proponents for a "conventional" origin suggest that normal magmatic processes were responsible for the body, whereas others argue that the body resulted from a meteor impact, which formed a large crater and activated deep-level magmatic processes. Since its proposal by Dietz (1964), this latter hypothesis has acquired increasing, but not universal, acceptance.

If correct, an impact origin for the Sudbury intrusion may have significant implications for finding additional similar deposits. The combination of events, including meteor impact, needed to generate a Sudbury-type intrusion may be so uncommon as to make the formation of similar deposits unlikely. Other deposits of this type may be scarce or even nonexistent, and thus analysis of tonnage and grade of the Sudbury nickel deposits would have little significance outside of the Sudbury region.

The Norilsk-Talnakh complex in the Arctic area of northwest Siberia (U.S.S.R.) is the only other major nickel-producing area in a stable tectonic setting. It is markedly different from Sudbury in that nickel-rich sulfides have accumulated within tholeiitic sills that have been contaminated by sulfur-bearing country rock (Gorbackev and Grinenko, 1973). No deposit data are available for this district. Except for the apparently geologically unique Sudbury intrusion, a general lack of data exists for deposits in stable tectonic settings. Thus, no grade and tonnage analysis for this group was attempted.

DEPOSITS IN AREAS THAT HAVE BEEN TECTONICALLY ACTIVE

If the Sudbury intrusion is discounted, deposits in areas that have been tectonically active host most of the world's nickel sulfide reserves. Differences among these deposits make their division into numerous subclasses possible. However, for the broader purposes of regional resources assessment, only two general subclasses are considered here.

KOMATIITES

By far, the most important subclass of deposits is associated with a relatively recently identified suite of mafic and ultramafic rocks called komatiites. The deposits in Botswana, Rhodesia, and western Australia and in the Thompson, Abitibi, and Ungava districts of Canada belong to this subclass. Some characteristic features of this magmatic suite are listed as follows (more complete discussions of the character and origin of this magma type are presented by Viljoen and Viljoen, 1969; Pyke and others, 1973; Brooks and Hart, 1974; Naldrett and Cabri, 1976; Arndt and others, 1979):

1. Komatiites commonly have a distinctive chemistry (a low FeO/FeO+MgO ratio, a low TiO_2 concentration, and a CaO/Al_2O_3 ratio of nearly 1) and a unique quench texture called spinefex, which is formed by skeletal blades and plates of olivine and pyroxene.
2. The apparent restriction of these nickel deposits to rocks older than 1.7×10^9 years suggests that the magmatic processes responsible for these deposits are no longer operating.

3. Experimental evidence (Green and others, 1975) indicates that these ultramafic flows were extruded at temperatures from 1,400–1,600° C. These temperatures imply that the geothermal gradients controlling komatiite formation were much steeper than those presently existing (Green, 1975).
4. Nickel deposits are associated with only the most magnesium-rich members of the komatiitic suite (Naldrett and Arndt, 1976).

Highly successful exploration models have been devised using the nickel sulfide-komatiite association. Exploration has been directed toward shield areas in which ancient orogenic belts and magnesium-rich ultramafic rocks exist. Particular attention is given to the basal contact where immiscible sulfides would most likely accumulate. Since discovery of the Kambalda (Australia) deposits in 1966, this model has been used to find many other deposits throughout western Australia. Deposits associated with komatiites are now known from the shield areas of Canada, Africa, and Australia. Additional deposits in these areas surely exist. Further, large shield areas, such as those in Greenland, Brazil, India, the U.S.A., and the U.S.S.R., have favorable rock types in which few or no nickel deposits have yet been discovered. Promising exploration targets are surely present in these areas. The wide geographic distribution of these deposits and the availability of grade and tonnage data make this deposit subclass particularly suitable for grade and tonnage analysis.

SMALL INTRUSIONS

The second subclass (small intrusions) for which statistical analysis of grade and tonnage was attempted contains several diverse types of deposits. Although division of these deposits into several smaller groups is possible, placing them together in a broad subclass makes a large and homogeneous population that is amenable to statistical analysis and use in regional resource assessments. The deposits are mostly small and low grade; thus they have not been significant producers of nickel, and little has been written about their geologic character. Most are in small- to medium-size, predominantly mafic intrusions that range in age from Precambrian to Tertiary. Their relatively large copper-to-nickel ratio (generally greater than one copper to five nickel) reflects their mafic composition and is particularly useful in distinguishing these deposits from those associated with the more ultramafic komatiites (Naldrett and Cabri, 1976). The Great Lake, Lynn Lake, and Giant Nickel deposits of Canada are examples of this subclass.

GENERAL CHARACTERISTICS

Although different in many details, different types of sulfide deposits are strikingly similar. Largely, this results from basically similar mechanisms of formation. Most nickel deposits associated with igneous rocks are believed to have been formed by separation of an immiscible sulfide phase within a crystallizing silicate melt. Because of the strong affinity of sulfur for metals, dense droplets of immiscible sulfides combine with metallic elements in the melt and settle toward the bottom of the magma. Commonly, massive metallic-sulfide deposits form in topographic or structural depressions at the magma-chamber base. Successively overlying the massive-sulfide ores are a zone of disseminated sulfides and a zone of barren silicates. Sulfide minerals within deposits commonly are pyrrhotite, pentlandite, chalcopyrite, and minor pyrite. In addition to nickel, many deposits contain significant amounts of copper and minor, but locally recoverable, amounts of cobalt, platinum-group elements, and selenium. Later deformation, metamorphism, or hydrothermal alteration may mobilize the sulfides and obscure the deposit's initial magmatic character.

Tonnage of nickel sulfide varies greatly and is influenced by many factors. Perhaps most important are (1) the size of the igneous complex (as size of the igneous complex increases, the potential for forming larger tonnage deposits generally also increases), (2) the nickel and sulfur content of the magma (the potential for larger tonnages increases as the nickel and sulfur content of the magma increases), (3) the size of the trap in which sulfides accumulate, (4) the nature of the magma circulation, and (5) postore deformation.

The grade of nickel sulfide deposits also varies, but it appears to be controlled principally by the crystallization history of the magma, which in turn is closely tied to the magma's primary sulfur and metal content. If the magma were saturated with sulfur before many silicates had crystallized, then an almost pure immiscible nickel sulfide phase could separate and concentrate to form a high-grade deposit. If, however, sulfur saturation were delayed, the immiscible sulfide phase would be intermixed with silicate crystals and lower grade sulfide deposits would form. Other factors locally important in determining grade involve the circulation system of the magma chamber, wallrock reactions, postmineralization mobilization of ore, and supergene alteration.

NICKEL-LATERITE DEPOSITS

The contribution of nickel-laterite deposits to the world nickel supply has been variable. In the late 1800's, production from New Caledonia deposits supplied most of the world's nickel. However, with the development of more easily processed sulfide ores from Sudbury, Canada, the contribution of laterite deposits declined. Today, nickel from laterite deposits represents about 20 percent of the world's production but more than 80 percent of identified world nickel reserves. With improved extraction technology and increasing demand for nickel, laterite deposits are assuming greater importance as a source of nickel.

Nickel laterite is soil formed in warm humid climates by chemical breakdown of ultramafic rocks. Two different ore types – oxide and silicate – are formed depending on the nature of the chemical alteration. Oxide ores contain approximately 0.8–1.5 percent nickel, which is in iron oxide (mostly goethite). These ores are the most common and represent the bulk of material currently being mined in Cuba, the Dominican Republic, and the Philippines. Nickel silicate ores are generally of higher grade (2–4 percent nickel). In these ores nickel is included in poorly defined hydrous magnesium silicate, commonly termed garnierite. Deposits of this type are currently being mined at Riddle, Oreg., and in New Caledonia. Both ore types are frequently found within the same deposit.

The formation of nickel laterite begins with the chemical weathering of ultramafic rocks. When immiscible sulfides are absent in a magma, nickel's strongest affinity is for the olivine and pyroxene crystal structure, and rocks composed largely of these minerals frequently have a relatively high primary nickel content (commonly 0.2–0.4 percent nickel). When exposed to a tropical climate, the ultramafic rocks break down through a series of complex hydrolysis reactions. Iron in solution readily oxidizes and precipitates to form a hard crust at the top of the weathering profile. Nickel, magnesium, and silica are more mobile and tend to be leached from the surface zone. Magnesium and silica concentrate toward the base of the soil profile or are carried away in solution while the downward moving ground water effects a less complete separation of the less soluble nickel from the iron-rich layer. If extensive separation of nickel is not achieved, as is common, then most of the nickel occurs with iron. Oxide laterite is formed. Upon more complete separation, nickel precipitates with magnesium and silica at the base of the weathering profile, and accumulations of hydrous silicate ore (garneirite) form (Golightly, 1979). Because of mineralogic differences, silicate ore tends to be richer in nickel than is oxide ore. Within most laterite, both ore types are generally present in varying amounts, and thus the classification of a deposit as oxide or silicate is somewhat arbitrary.

The factors that most directly affect tonnage of laterite deposits are

1. the size of the underlying ultramafic body;
2. the duration and intensity of the weathering process;
3. the size of the "trap" that may pond nickel-bearing ground-water solutions; and
4. the physical erosion and dissection of the deposit.

Grade of nickel laterite is principally controlled by

1. the concentration of nickel in the parent ultramafic rock;
2. the mineralogy of the parent rock; and
3. the duration and intensity of the weathering process.

GENERAL GEOLOGIC AND ECONOMIC CONSIDERATIONS CONCERNING CONTROLS ON DEPOSIT GRADE AND TONNAGE

The geologic factors that control the relationship of deposit tonnage to grade may be very complex. When each deposit is examined individually, it becomes evident that many factors affect either grade alone or tonnage alone. Some factors, however, influence both grade and tonnage. A simplified example, involving only one factor, may be used to illustrate this. If an ore-forming system is closed, then the total amount of metal available to form a deposit is fixed. Therefore, a relationship between the potential grade and tonnage within that deposit is established because the deposit grade equals the value for the amount of metal in a deposit divided by that for deposit tonnage. Potential values of grade and tonnage define a negative sloping line (fig. 1*A*); the actual grade and tonnage of the deposit makes a point on this line. The relationship of potential grade to potential tonnage within deposits is, of course, much more complex. The important point is that within any given ore-forming system, the factors determining an individual deposit's grade may not be entirely independent of those controlling a deposit's tonnage.

However, attempts to extrapolate potential grade and tonnage relationships in individual deposits to those for a regional or global population of similar deposits may encounter serious problems. Usually each ore deposit is formed in a geologic system that is isolated from systems forming other similar deposits. Thus, the tonnage and grade of a deposit in one system will be unaffected by that in other systems. They will, therefore, tend to be independent. This independence of systems is illustrated in figure 1*B*, where four similar but isolated and different-sized ore systems are shown (*a*, small, to *d*, large); among these deposits no grade and tonnage relationship exists or should be expected.

From the foregoing, it is apparent that no simple generalizations can be made for the presence or absence of grade and tonnage relationships within ore deposits. For some deposit types, independent geologic factors

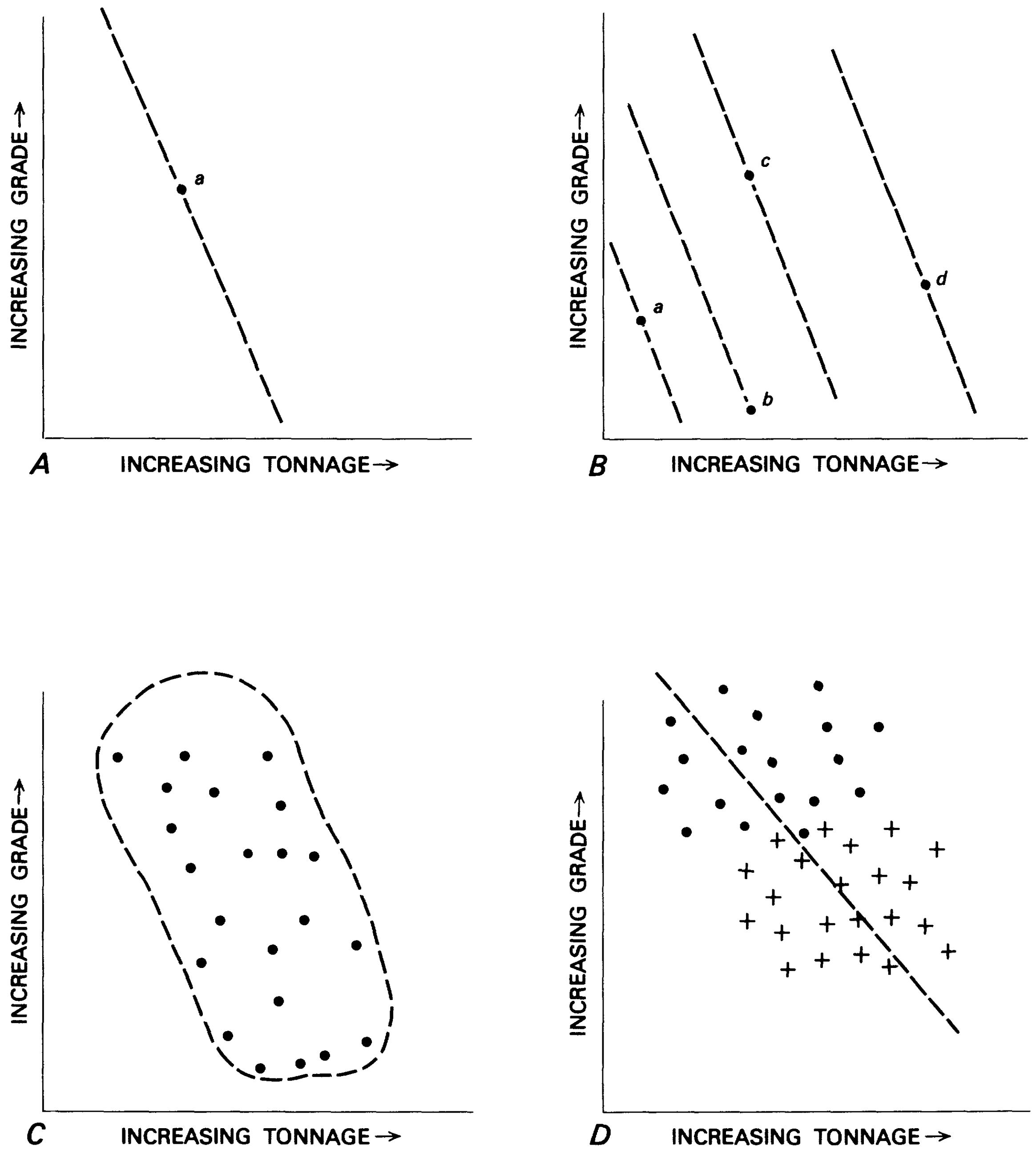

FIGURE 1.–Log-log plots illustrating several hypothetical tonnage and grade relationships. *A*, Closed ore system. The dashed line shows the potential values for deposit grade and tonnage; the dot represents the actual deposit grade and tonnage. *B*, Four separate ore systems similar to that in *A*. Because each system is isolated from the other, grade and tonnage among the actual deposits (*a*,*b*,*c*,*d*) are independent; no correlation exists. *C*, Deposit type in which chemical and physical factors (such as mineralogy) place limits on deposit tonnage and grade and thus tend to restrict the part of the plot in which deposits fall (dots). Depending on the envelope (dashed line) produced by the restrictions, a grade-tonnage correlation may be induced. *D*, Two different deposit types (dots and crosses) tend to occupy discrete areas of the grade-tonnage plot. Although tonnage and grade are independent within each deposit type, an inverse grade and tonnage correlation exists when the two deposit types are considered together.

quite obviously affect only grade or tonnage and thus tend to make these two variables independent. For example, in laterite deposits the starting size of the ultramafic parent rock and subsequent physical erosion are particularly important factors affecting tonnage, but these factors do not significantly influence grade, which is largely controlled by chemical weathering. Thus, within lateritic deposits, one might reasonably expect a general independence of grade and tonnage.

In sulfide deposits, however, the relation appears to be more complex. The interaction between ore-forming and concentrating processes is poorly known. For example, the primary concentration of sulfur and nickel in the magma may influence both the tonnage and grade within an individual deposit. Among a group of deposits, the chemical and physical constraints on the emplacement of intrusions and the subsequent formation of sulfides may place limits on the grade and tonnage a deposit may have. Sulfide mineralogy, for example, controls the maximum grade of a deposit. Depending on the nature of the restrictions, deposits may be confined to a part of the grade and tonnage plot and an inverse grade-tonnage relationship might form (fig. 1*C*).

Two general comments should be made concerning the foregoing. First, it is necessary to compare only deposits of the same type. Because deposit mineralogy, mode of formation, and other variables may restrict the grade and tonnage values of a given deposit, mixing of two or more deposit types in the data may induce an artificial grade and tonnage correlation (fig. 1*D*). This mixing of different deposit types can often be detected statistically, although it may be difficult to identify and separate different types of deposits. Second, a variety of economic and operational factors generate uncertainties in the grade and tonnage data; some factors that may tend to impose an inverse grade and tonnage correlation are listed as follows:

1. Very low-grade, small deposits are not profitable to mine and consequently may not be examined or reported.
2. Because it is economically more profitable, a large deposit may be studied, reported on, and mined before a smaller deposit of the same grade is.
3. For small deposits, reserves are commonly developed for only 5 to 10 years, and thus the resultant tonnage estimate is biased downward. For larger deposits, the scale of operation requires more complete estimates of grade and tonnage.
4. Some reported grade and tonnage may include all of the mineralized rock, whereas other estimates are restricted by artificially established cutoff grades. Frequently, no clear distinction between mineralized and barren rock exists. An accurate assessment of what each reported value means is usually not possible.

These factors are related in that they bias the sampling of what actually exists. Particularly, the lack of data on low-grade small deposits tends to produce an apparent inverse correlation. Despite these problems and uncertainties, the tonnage and grade relationships obtained may still provide a predictive base for resource estimates if one can expect that the basic nongeologic factors that influence grade and tonnage relationships among deposits today will also be influencing the relationships among deposits found in the future.

GRADE AND TONNAGE ANALYSIS

Statistical analysis was carried out on three specific nickel-deposit types: deposits associated with komatiitic rocks, nickel sulfide deposits in small intrusions, and nickel-laterite deposits. Data from each type were first analyzed by fitting frequency distributions to both deposit grade and deposit tonnage. This was necessary to (1) insure that the population was homogeneous, (2) provide empirically tested theoretical distributions that can be used in regional resource assessments, and (3) insure that the assumptions required for testing the correlations among grade and tonnage can be met. After investigating the frequency distributions separately for grade and tonnage, tests were made to see if the two variables were independent.

The adequacy of lognormal distributions as models of grade and tonnage was tested by fitting theoretical normal distributions to the logarithms of the data and then testing the beta statistics (moments) of the observed distributions, $\sqrt{b_1}$ (asymmetry) and b_2 (skewness), against expected values of $\sqrt{\beta_1}=0.0$ and $\beta_2=3.0$. Once the distributions of grade and tonnage were investigated, the correlation coefficient (r) of the variables was calculated and used to test the hypothesis that grade and tonnage were independent ($r=0$). All tests were made at the 5-percent probability level.

NICKEL SULFIDES ASSOCIATED WITH KOMATIITIC ROCKS

Data on average nickel grade and tonnage were collected for 52 nickel sulfide deposits associated with komatiitic rocks (fig. 2.). The data include deposits from three continents (Africa, Australia, North America). Comparison of the observed distributions of grade and tonnage of these deposits with theoretical lognormal frequency distributions indicates that, at the 5-percent probability level, lognormal distributions adequately model the deposit grade and tonnage. Table 1 presents the means, median, and standard deviation of the observed distributions and the beta statistics. In the previous section, economic factors that tend to impose

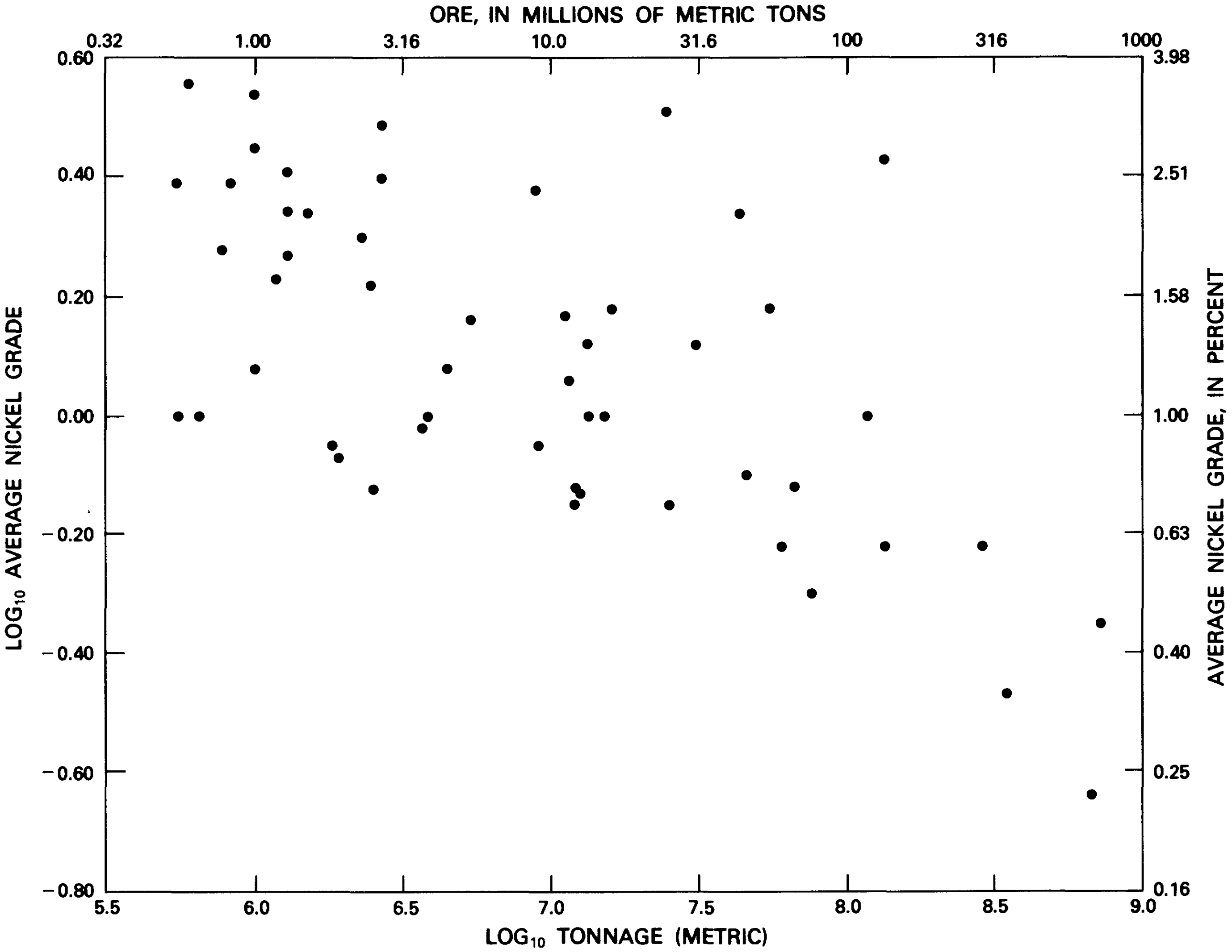

FIGURE 2.—Grade and tonnage of nickel sulfide deposits associated with komatiitic rocks.

TABLE 1.—*Summary statistics for grade and tonnage of nickel sulfide deposits associated with komatiitic rocks*

	Arithmetic		Logarithmic data (base 10)				
Variable	Number of deposits (n)	Median	Mean	Standard deviation	$\sqrt{b_1}$ (assymmetry)	b_2 (skewness)	Correlation coefficient (r)
Tonnage, metric _____	52	8.49×10^2	6.93	0.86	0.49	2.31	−0.62
Nickel grade, percent ____	52	1.24	.09	.27	−.29	2.65	−0.62

an inverse relationship on reported grade and tonnage were discussed. Often these economic effects are revealed by truncation of data for low grade and tonnage in observed distributions and by skewness of the observed distributions in the direction of higher grade and tonnage, even though the variables have been transformed by taking logarithms. Examination of figure 2 suggests that economic bias probably has resulted in the truncation of data from some low-tonnage deposits.

Because the observed distributions of tonnage and average grade are not significantly different from lognormal distributions, a test can be made to see if the two variables are independent. The Pearson product moment correlation coefficient (r; table 1) was found to be significantly different from zero, indicating that a negative correlation exists between the two variables; as deposit grade increases, deposit tonnage decreases.

Thus, the lognormal distribution's fit to deposit average grade and tonnage, together with the correlation coefficient (r), seem to provide an adequate model of komatiitic nickel deposits. However, as demonstrated by Singer and others (1975), some deposit types show regional differences in average grade and tonnage. Such differences may be an important consideration for regional assessment of mineral resources.

The 52 deposits used in the model are in nine different regions; of this group, 41 of the deposits are in four

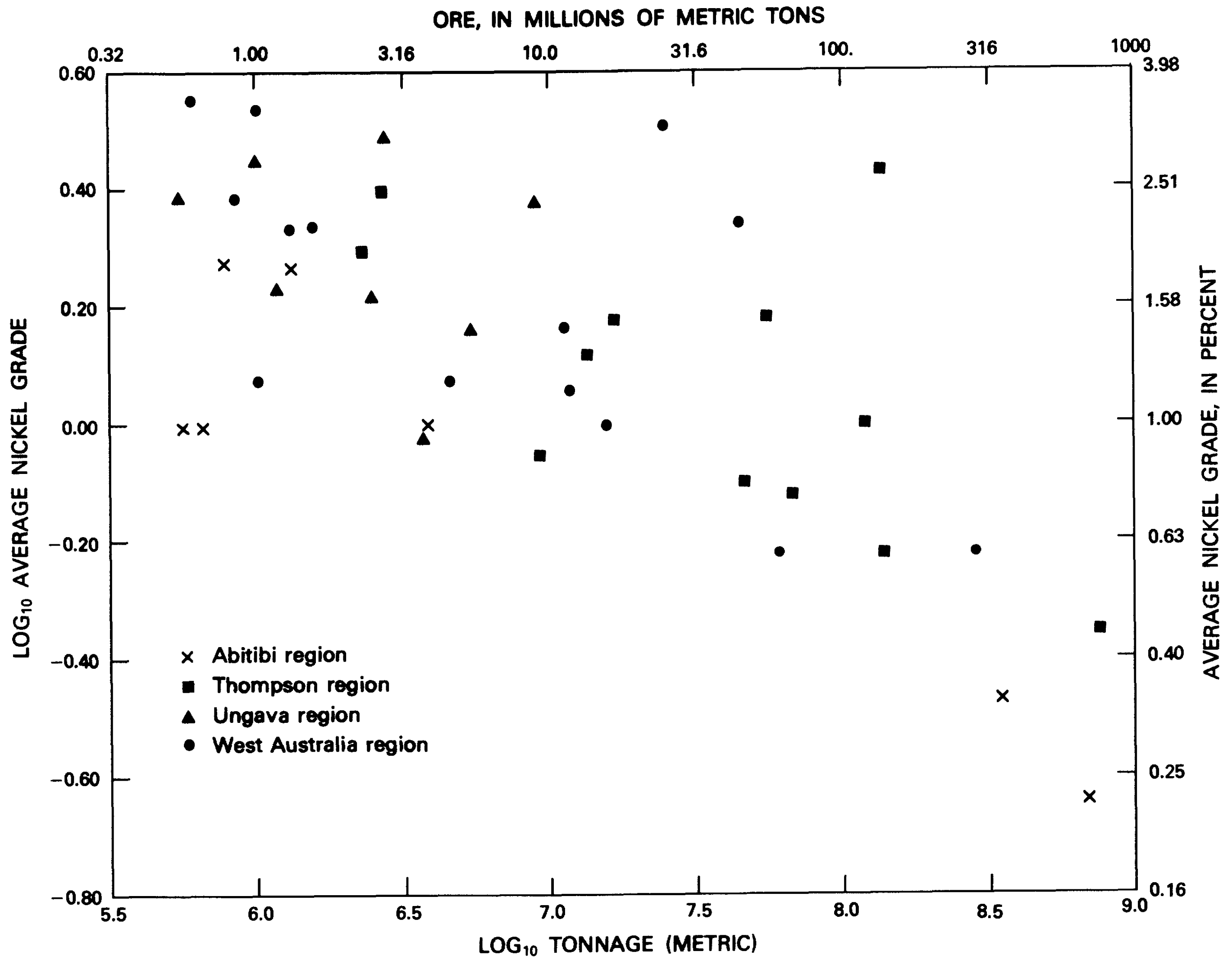

FIGURE 3.—Grade and tonnage of nickel sulfide deposits in komatiitic rocks from four regions.

regions. Because the five remaining regions contain at most four deposits each, they were excluded from an analysis of regional differences. The average nickel grade and tonnage of deposits from the four regions are plotted in figure 3, and summary statistics for the observed distributions of both variables for each region and for all regions combined are presented in table 2.

The beta statistics for four regions are not significantly different from values expected from theoretical lognormal distributions. However, the average nickel grade of the four groups together is significantly skewed. Thus, the data from the four regions meet one of the requirements of most statistical methods (such as analysis of variance) for testing for population (regional) differences. Another requirement of most methods is that variances (and covariances) of the regions be approximately equal. Standard deviations (the square root of variance) of average grade and tonnage within each region (table 2) vary by about an order of magnitude. The large differences in the standard deviations plus the relatively small sample size of each region suggest that the data probably do not meet the requirements of techniques such as the analysis of variance. In such situations a quality-control chart, showing grade and tonnage, can aid in the interpretation of differences of the means of variances.

Figure 4 presents the means of average grade and tonnage and the means plus and minus two standard errors of the means for the deposits in the four regions. Figure 4 reveals that differences between regions can be quite large. Given that large regional differences exist in the average grade and tonnage of deposits, the question

TABLE 2. – *Summary statistics for grade and tonnage of nickel sulfide deposits in komatiitic rocks from each of four regions and from the regions as a pooled group*

[All data except "n" are expressed as logarithms. $\sqrt{b_1}$, asymmetry; b_2, skewness]

Region	Number of deposits (n)	Mean of log Ni grade	Standard deviation	$\sqrt{b_1}$	b_2	Mean of log tonnage	Standard deviation	$\sqrt{b_1}$	b_2	Correlation coefficient (r)
Abitibi	7	-0.0795	0.1224	-0.5995	1.9764	6.7858	1.7681	0.8285	1.8589	-0.9166
Thompson	12	.0642	.0600	-.0152	1.9694	7.5433	.5539	-.1045	2.2541	-.6116
Ungava	8	.2867	.0288	-.5290	2.2301	6.3590	.1622	-.1050	1.9799	-.2989
West Australia	14	.2117	.0678	-.2937	1.9770	6.8007	.6932	.4256	2.080	-.6417
Four regions	41	.1334	.0781	[1]-.6599	3.0858	6.9293	.8587	.5050	2.1266	-.6633

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[1] Significant at 5-percent level

arises: Are the correlation coefficients of average grade and the tonnage of deposits within regions significantly different? The correlation coefficients (table 2) of the variables for the regions were tested to see if they were different; the test could not establish significant differences among the correlation coefficients for the four regions. These results suggest that although the regions differ in the average grade and tonnage of deposits, the overall process that related the two variables may be the same. Thus, statistical results are consistent with the inference that basically the same geological processes formed the deposits in the four regions.

NICKEL SULFIDES ASSOCIATED WITH SMALL INTRUSIONS

Nickel sulfide deposits associated with komatiitic rocks present one type of deposit found in orogenic belts; another type of deposit is associated with a variety of small to medium-sized intrusions of predominantly mafic composition. In many places, these deposits are associated with a diverse group of intrusions that in-

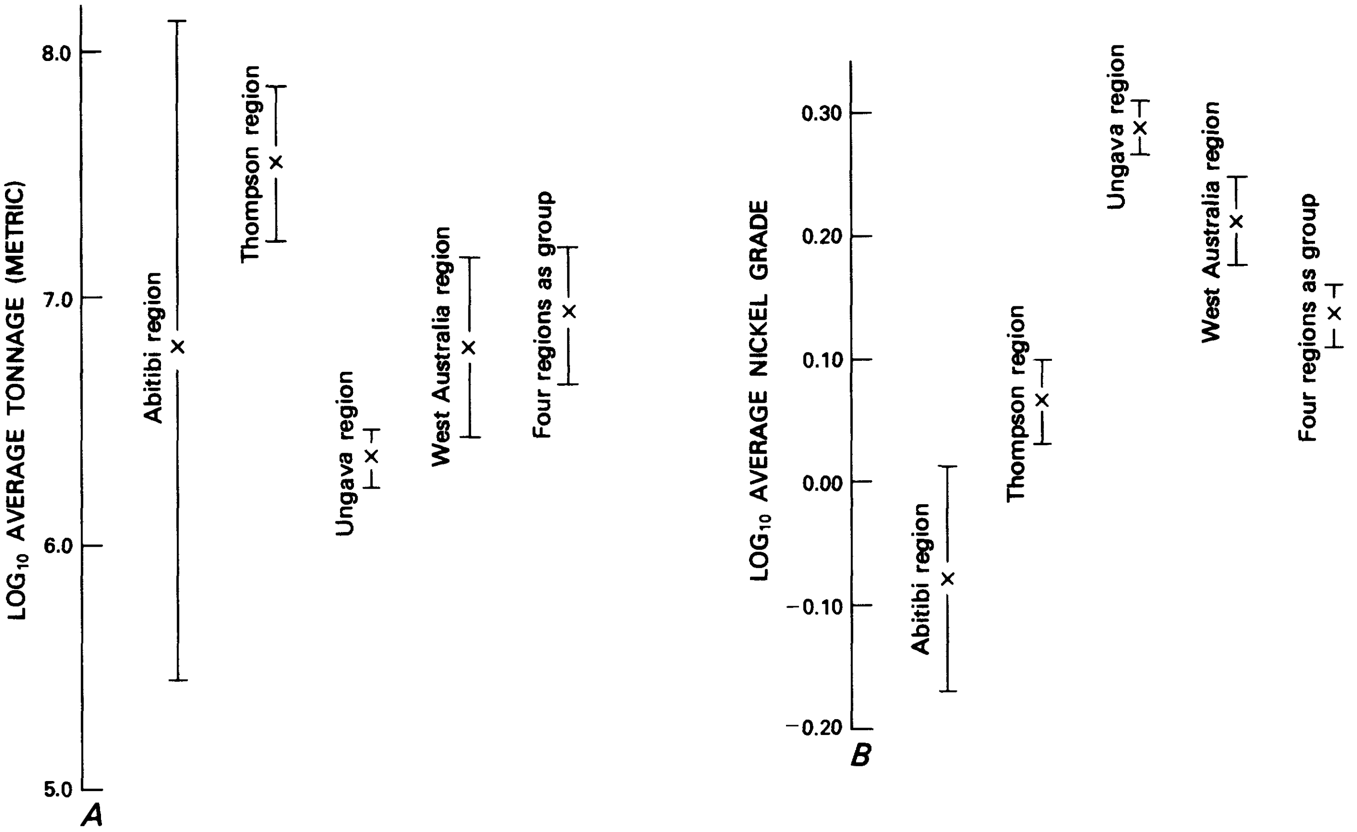

FIGURE 4. – Quality-control chart (a plot of means and standard errors) of tonnage and grade for nickel sulfide deposits in komatiitic rocks. Data are from four regions, plotted both as a group and as separate areas. X represents the means; bar extensions indicate plus and minus 2 stand ard errors. A, For tonnage. B, For grade.

TABLE 3.—*Summary statistics for grade and tonnage of nickel sulfide deposits associated with small intrusions*

	Arithmetic		Logarithmic data (base 10)				
Variable	Number of deposits (n)	Median	Mean	Standard deviation	$\sqrt{b_1}$ (assymmetry)	b_2 (skewness)	Correlation coefficient (r)
Tonnage, metric	50	1.27×10^6	6.10	0.51	0.15	3.33	−0.09
Nickel grade, percent	50	.60	−.22	.23	−.23	3.00	−0.09

clude differentiated sills, zoned intrusions, and breccia pipes. Data on average nickel grade and tonnage were collected for 50 such deposits (fig. 5), most of which are in Canada. Summary statistics (table 3) of the observed frequency distributions of average grade and tonnage are not significantly different from values expected for samples from theoretical lognormal distributions. A test of the correlation coefficient (r) indicates that the observed variables may be regarded as independent. Thus statistical tests suggest that values for average grade and tonnage of nickel sulfide deposits associated with small intrusions are independent variables that fit theoretical lognormal distributions.

COMPARISON OF NICKEL SULFIDE DEPOSITS IN SMALL INTRUSIONS WITH THOSE ASSOCIATED WITH KOMATIITIC ROCKS

The two types of nickel sulfide deposits were defined largely by their geologic characteristics. A plot of average grade and tonnage of deposits of both types (fig. 6) demonstrates several points:

1. A marked difference exists in average grade and tonnage of the two deposit types. A median nickel grade of the deposits associated with komatiitic rocks (1.24 percent) is about twice that of the deposits associated with small intrusions (0.60 percent). The median tonnage of the deposits associated with komatiitic rocks (8.49×10^6 metric tons) is about 6½ times that of the deposits associated with small intrusions (1.27×10^6 metric tons).
2. A difference exists in correlation coefficients of the variables in the two groups.

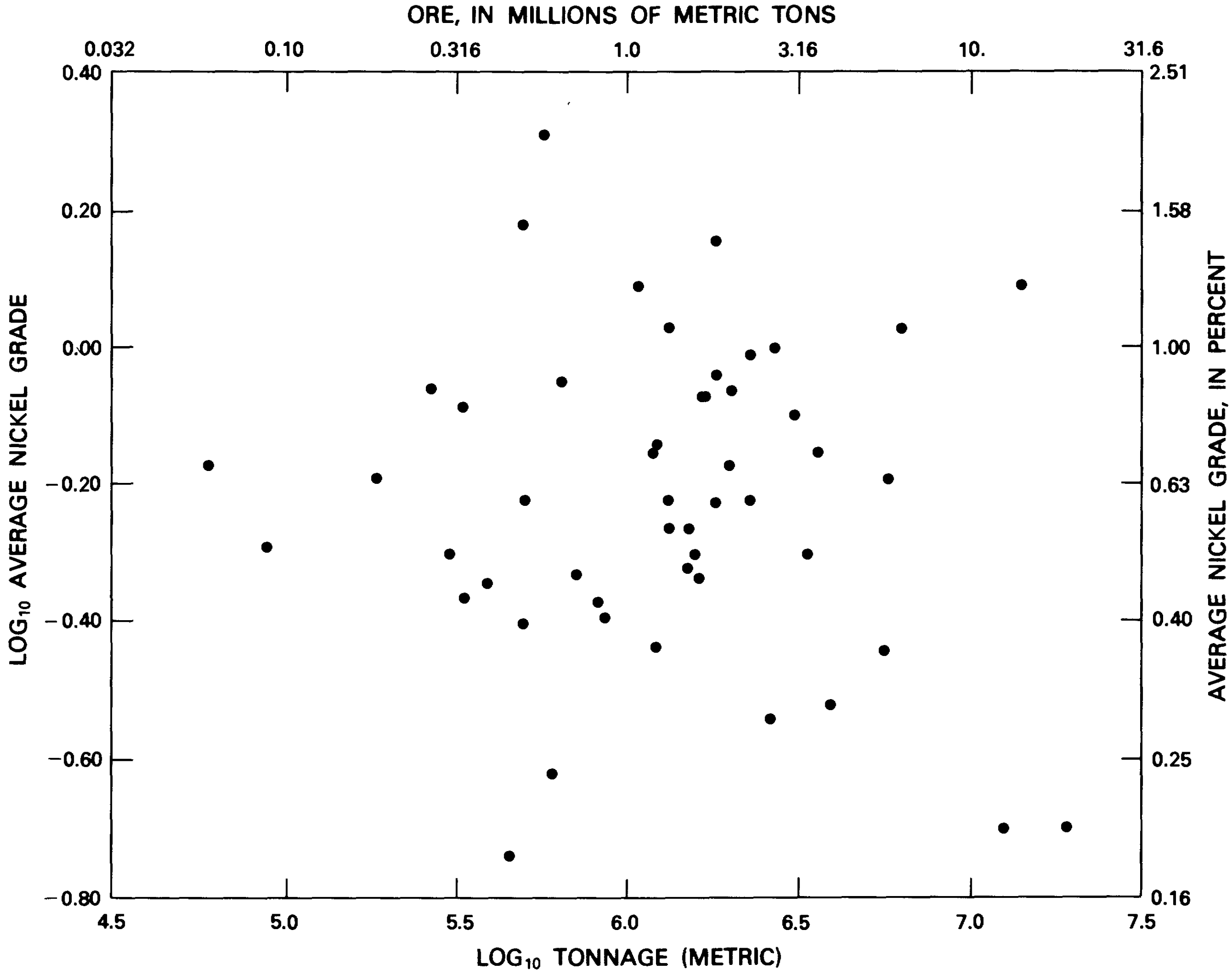

FIGURE 5.—Grade and tonnage of nickel sulfide deposits associated with small intrusions.

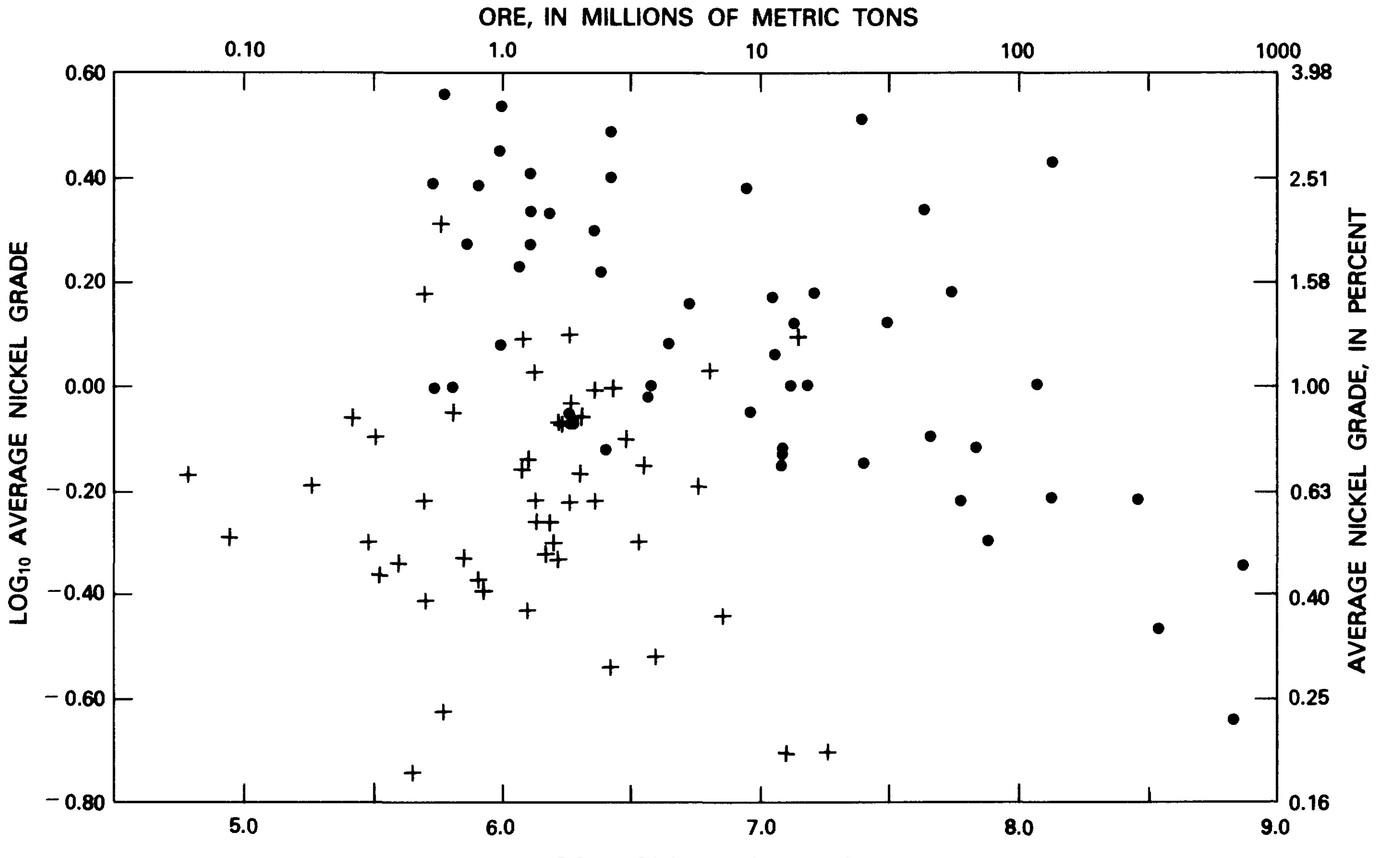

FIGURE 6. – Grade and tonnage of two types of nickel-sulfide deposits. Deposits associated with komatiitic rocks are represented by a dot (•), and those associated with small mafic intrusions are represented by a cross (+).

Summary statistics for sulfide deposits of both types considered together (table 4) show a significant skewness of deposit-tonnage data. This skewness can be interpreted as indicating that the data set is heterogeneous – that is, geologically different deposit types have been mixed. Absence of skewness where each subgroup is considered separately lends statistical support to the geologic distinction between these two deposit types.

TABLE 4. – *Summary statistics for grade and tonnage of nickel sulfide deposits*

	Arithmetic		Logarithmic data (base 10)				
Variable	Number of deposits (n)	Median	Mean	Standard deviation	$\sqrt{b_1}$ (assymmetry)	b_2 (skewness)	Correlation coefficient (r)
Tonnage, metric	102	3.34×10^6	6.52	0.82	[1]0.80	3.43	-0.0531
Nickel grade, percent	102	.87	-.06	.30	-.03	2.62	-0.0531

[1] Significant at the 1-percent level.

NICKEL-LATERITE DEPOSITS

Average nickel grade and tonnage data for 64 nickel-laterite deposits from six continents were collected. The data are plotted in figure 7, and summary statistics for the observed distributions of average nickel grade and tonnage of the laterite deposits are presented in table 5. Beta statistics indicate that the observed distribution of average grades is significantly skewed toward deposits having high average grades. Whereas the observed frequency distribution of tonnage can be adequately modeled by a lognormal distribution, the observed frequency distribution of grade cannot.

TABLE 5. – *Summary statistics for grade and tonnage of nickel-laterite deposits*

	Arithmetic		Logarithmic data (base 10)				
Variable	Number of deposits (n)	Median	Mean	Standard deviation	$\sqrt{b_1}$ (assymmetry)	b_2 (skewness)	Correlation coefficient (r)
Tonnage, metric	64	40.48×10^6	7.61	0.60	-0.05	3.42	-0.211
Nickel grade, percent	64	1.41	.15	.10	[1].69	3.72	-0.211

[1] Significant at the 5-percent level.

Skewness of average grades of nickel-laterite deposits could have several sources. First, it may result from economic factors. Much of the data have come from deposits in remote locations, and higher operating costs

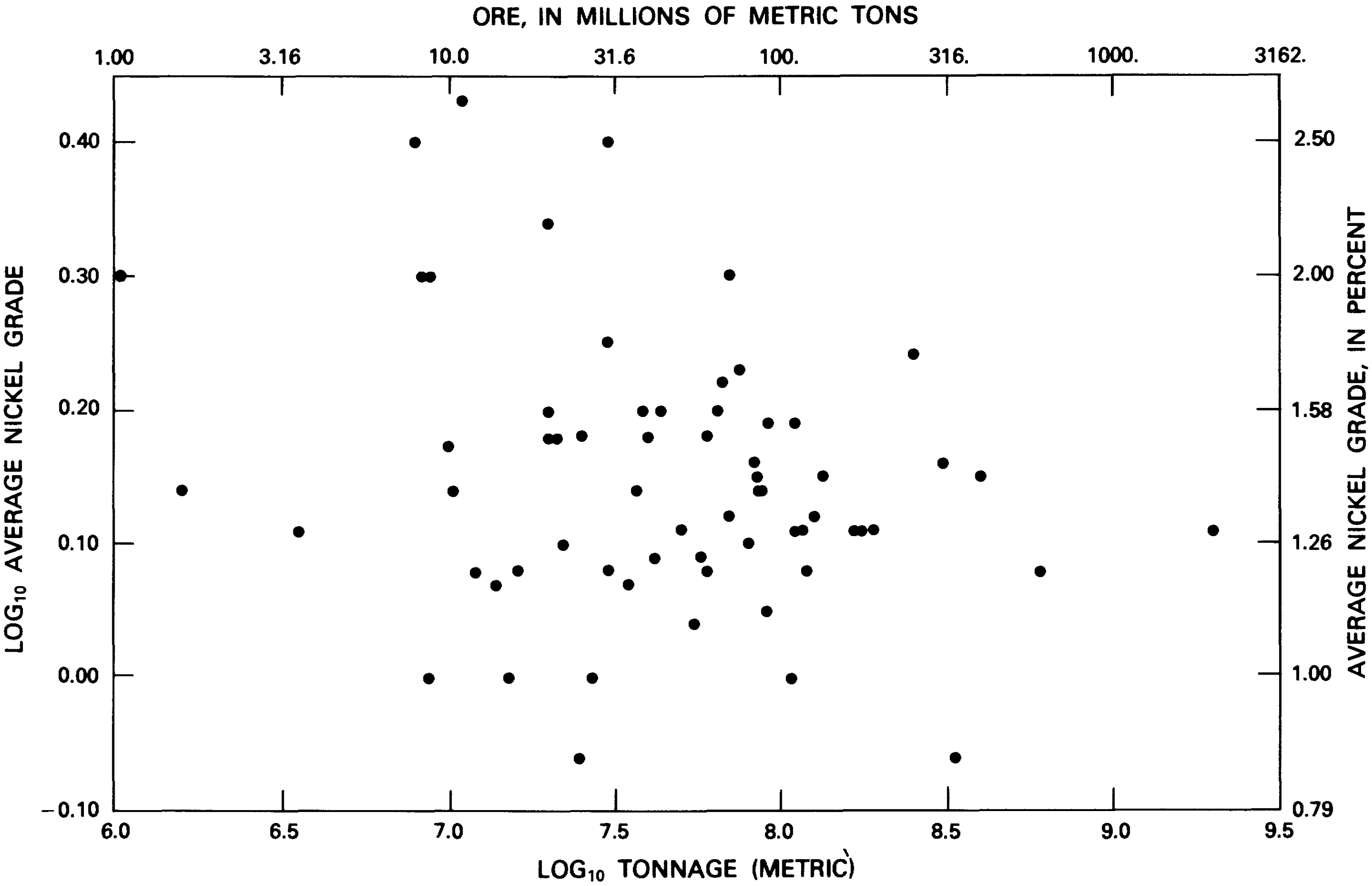

FIGURE 7.—Grade and tonnage of nickel-laterite deposits.

TABLE 6.—*Summary statistics for grade and tonnage of oxide nickel-laterite deposits*

	Arithmetic		Logarithmic data (base 10)				
Variable	Number of deposits (n)	Median	Mean	Standard deviation	$\sqrt{b_1}$ (assymmetry)	b_2 (skewness)	Correlation coefficient (r)
Tonnage, metric _____	54	45.18×10^6	7.65	0.63	−0.21	3.35	−0.13
Nickel grade, percent ____	54	1.36	.13	.08	.19	3.59	−0.13

for such deposits might force higher cutoff grades than for less remote deposits that have lower operating costs. This would tend to raise the average grade and reduce the tonnage of these deposits. Second, the skewness in average grade can result from mixing of more than one type of laterite deposit. As previously mentioned, nickel-laterite deposits can be geologically divided into two end-member groups on the basis of mineralogy. These are silicate deposits, which have garnierite as the principal nickel mineral, and oxide deposits, in which nickel is with iron oxides. Although these two types grade into one another, the ore formation represents different degrees of physical and chemical interactions. Thus, the skewness in average grade can be caused by mixing deposits of silicate and oxide ores.

In figure 8, only deposits that do not contain significant amounts of silicate ore (garnierite) are plotted; summary statistics are shown in table 6. Beta statistics for the observed distributions of average grade and tonnage of the deposits are not significantly different from values expected from theoretical lognormal distributions. The correlation coefficient of average grade and tonnage for the oxide nickel-laterite deposits is not significantly different from zero. Thus, average grade and tonnage of nonsilicate nickel-laterite deposits follow theoretical lognormal distributions and act as independent variables.

SUMMARY AND CONCLUSIONS

In this study we have investigated the distribution of and relationships among average grades and tonnage of nickel deposits belonging to several geologically defined deposit types. Consideration of the geologic factors influencing grade and tonnage suggests that for nickel-bearing laterite deposits no relationship between the two variables should be expected. For sulfide deposits, the factors are too complex to determine the correlation between tonnage and grade.

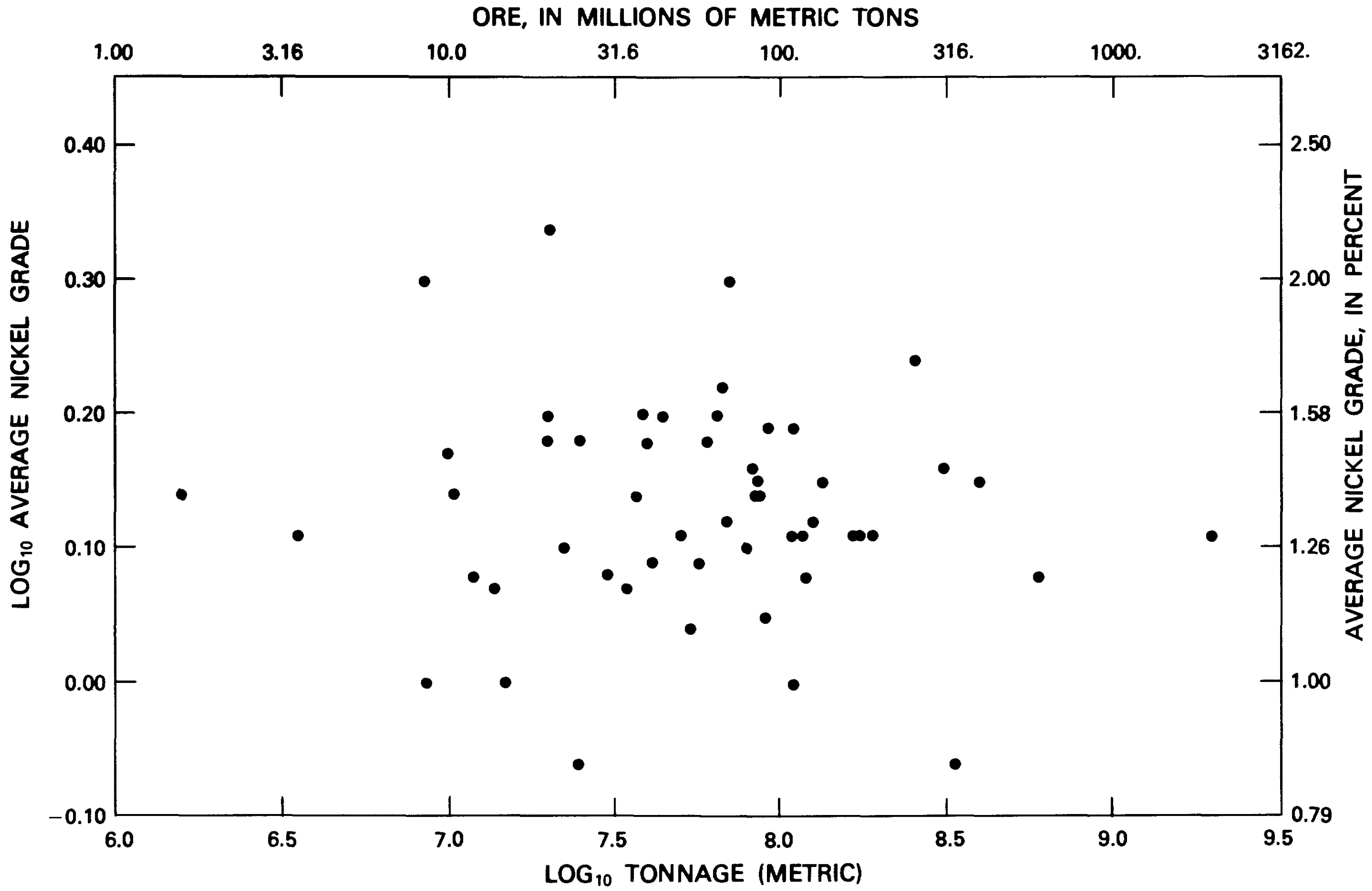

FIGURE 8.—Grade and tonnage of oxide nickel-laterite deposits.

Two types of sulfide deposits were defined on the basis of associated host rocks. Within deposits associated with komatiitic rocks and those associated with small orogenic intrusions, the lognormal distribution was found to be an adequate model for average grade and tonnage of deposits. However, the relationships between grade and tonnage in both deposit types are quite different. For deposits associated with komatiites, deposit grade correlates inversely with tonnage. Among deposits in small orogenic intrusions, grade and tonnage are independent. Further analysis of the komatiite association reveals that regional differences exist for average grade and tonnage of deposits but that no significant regional difference exists in the correlation coefficients that relate tonnage to grade. Regional differences of this type have important implications concerning the overall geologic controls that determined the formation of ore deposits and concerning the distribution of undiscovered ore deposits that might be predicted while making regional land assessments.

Initially, the lognormal distribution model was rejected for laterite deposits because of the skewness of deposit grades. Possible causes of this skewness were economic bias against low-grade deposits and mixing the data for two different deposit types. The latter possibility was examined by removing data for deposits in which significant amounts of silicate ore (garnierite) were present. Analysis of the low-garnierite deposits indicates that lognormal distributions are adequate models of both grade and tonnage and that laterite-deposit grade is independent of deposit tonnage. Statistical analysis confirmed this independence of grade and tonnage that was inferred from an assessment of the geological factors controlling deposit tonnage and grade.

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