Volcanogenic Massive Sulfide Deposits of the World—Database and Grade and Tonnage Models

By Dan L. Mosier, Vladimir I. Berger, and Donald A. Singer

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Volcanogenic Massive Sulfide Deposits of the World—Database and Grade and Tonnage Models

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Introduction

Grade and tonnage models are useful in quantitative mineral-resource assessments. The models and database presented in this report are an update of earlier publications about volcanogenic massive sulfide (VMS) deposits (Mosier, Singer, and Salem, 1983; Cox, 1986; Singer, 1986a-c; Singer and Mosier, 1986a, b). These VMS deposits include what were formerly classified as kuroko, Cyprus, and Besshi deposits. The update was necessary because of new information about some deposits, changes in information in some deposits, such as grades, tonnages, or ages, revised locations of some deposits, and reclassification of subtypes. In this report we have added new VMS deposits and removed a few incorrectly classified deposits. This global compilation of VMS deposits contains 1,090 deposits; however, it was not our intent to include every known deposit in the world. The data was recently used for mineral-deposit density models (Mosier and others, 2007; Singer, 2008). In this paper, 867 deposits were used to construct revised grade and tonnage models. Our new models are based on a reclassification of deposits based on host lithologies: Felsic, Bimodal-Mafic, and Mafic volcanogenic massive sulfide 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 occur in distinct geologic settings that can be identified from geologic maps. 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 different features are. Well-designed deposit models allow geologists to deduce possible mineral-deposit types in a given geologic environment and economists to determine the possible economic viability of these resources. Thus, mineral-deposit models play a central role in presenting geoscience information in a useful form to policy makers. The foundation of mineral-deposit models is information about known deposits. The purpose of this publication is to present the latest geologic information and newly developed grade and tonnage models for VMS deposits in digital form.

This publication contains computer files with information on VMS deposits from around the world. It also presents new grade and tonnage models for three subtypes of VMS deposits and a text file allowing locations of all deposits to be plotted in geographic information system (GIS) programs. The data are presented in FileMaker Pro and text files to make the information available to a wider audience. 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, we provide new grade and tonnage models and analysis of the information in the file. Finally, the fields of the data file are explained. Appendix A gives the summary statistics for the new grade-tonnage models and Appendix B displays the country codes used in the database.

Rules Used

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

VMS deposits consist of a generally conformable, massive body of massive sulfides, which may or may not be zoned into stratigraphic copper- and zinc-lead-rich sections. An underlying stockwork or feeder zone may or may not be present. The massive lens may grade laterally or vertically into semimassive, brecciated, or disseminated mineralization, but is contained within the immediate host rocks (for example, Kamikita, Japan; Joma, Norway). There may be multiple massive lenses that are stacked stratigraphically above one another (for example, Arctic, Alaska, USA; Rambler, Newfoundland, Canada), or there may be multiple lenses spaced out along a single horizon (for example, Hanaoka, Japan; Golden Grove, Western Australia). The deposits may have parts containing skarn (for example, Storliden, Sweden) or veins (for example, Fox, Manitoba, Canada; Baskoy, Turkey). Deposits that are primarily veins or skarns were excluded from this database.

An important consideration at the data-gathering stage is the question of what the sampling unit should be. Grade and tonnage data are available to varying degrees for districts, deposits, and mines. For the deposits in this file, the following spatial rule was used to determine which ore deposits were combined. All mineralized rock within 500 meters was combined into one deposit. For example, in this report Horne and Quemont in Quebec, Canada, are combined into one deposit, and Jerome in Arizona, USA, has been treated as two separate deposits, United Verde and United Verde Extension, because of the 500-meter rule. Such an operational spatial rule is necessary for defining deposits because we must be able to classify deposits in regions with highly variable geologic information and to avoid bias in estimating undiscovered deposits in resource assessments in areas where detailed spatial information is lacking. The 500-meter rule was developed to insure that deposits in grade and tonnage models correspond to deposits as geologic entities. Rules such as the 500-meter rule used here are essential to an internally consistent assessment system where the estimated number of undiscovered deposits is consistent with the grade and tonnage model.

An ore deposit is considered uneconomic when the tonnage is too small or the grades are too low to make mining and ore processing feasible. A deposit presently considered to be uneconomic may have been economic at earlier times when metal prices were higher or the cost of extraction was lower. For example, many of the VMS deposits that were mined in the Spanish Iberian Pyrite Belt by the Romans (27 B.C. to 395 A.D.) were small, high-grade deposits that are considered uneconomic by current standards. VMS deposits occurring as small pods, containing only a few hundred or a few thousand metric tons of ore, were mined. Because these small bodies would not currently be explored for and mined, we used an arbitrary cut-off of 10,000 metric tons to exclude them. Likewise, if we considered a particular grade to be too low, or anomalously high, it was excluded from the grade fields of the database, but is mentioned in the comments field.

Deposits included here must be associated with submarine volcanic rocks in a sequence of volcanic and sedimentary rocks. These volcanic rocks may include lava flows, pyroclastics, or volcaniclastic rocks; however, it is not required that they be the only host rocks of the deposit. A VMS deposit may be entirely enclosed by sedimentary rock units. These deposits may grade into a sedimentary exhalative type of deposit when volcanic rocks are absent in the stratigraphic column. VMS deposits are associated with volcanic rock compositions ranging from rhyolite to basalt, and they are formed in different paleotectonic environments (intra-arc basins, back-arcs, midocean ridges, and within plate rift zones). We chose to use a lithologic classification scheme for these deposits because of the availability of lithology information from geologic maps. We used the silica-based compositions for volcanic rocks to classify the volcanic host rocks, or their metamorphic equivalents, as follows: basalt <54 percent, andesite 54–62 percent, dacite 62–67 percent, rhyodacite 67–71 percent, and rhyolite >71 percent (Gelinas and others, 1977). In the absence of chemical compositions, we used the following general rules for protoliths of metavolcanic rocks.

· Sericite-muscovite-quartz schist, phyllite, or gneiss	· rhyolite
· Biotite-sericite-quartz schist, phyllite, or gneiss	· rhyodacite to dacite
· Sericite-chlorite-quartz schist, phyllite, or gneiss	· dacite
· Biotite-chlorite-quartz schist, phyllite, or gneiss	· dacite
· Hornblende-chlorite schist, phyllite, or gneiss	· andesite
· Pyroxene-chlorite schist, phyllite, or gneiss	· andesite
· Hornblende amphibolite	· andesite to basalt
· Pyroxene amphibolite	· basalt

Some deposits thought by some investigators to be VMS deposits were excluded from this compilation when there were uncertainties with the assumed metamorphic protoliths, or when they were classified by other investigators as sedimentary exhalative deposits (for example, Ducktown, U.S.A.; Mofjel and Bleikvassli, Norway).

Classification of Volcanogenic Massive Sulfide Subtypes

New grade and tonnage data and selected geologic information on worldwide VMS deposits were compiled into a database with the purpose of updating the grade and tonnage models that were initially published in Cox and Singer (1986) (table 1). In the bimodal volcanic sequences recognized in the Urals, the greenstone belts in Canada, and elsewhere, new subtypes of VMS deposits have been proposed (MacGeehan and MacLean, 1980; Sillitoe, 1982; Morton and Franklin, 1987; Lentz, 1998; Prokin and Buslaev, 1999; Barrie and Hannington, 1999; Franklin and others, 2005). In these papers, terms such “bimodal-mafic” and “bimodal-felsic,” with or without a “siliciclastic” component, were used to classify the VMS deposits believed to have formed in rifted volcanic-arc settings. In this study, we test the grades and tonnages of these VMS subtypes to see if they could be developed into new grade and tonnage models.

We arrived at the three final VMS grade and tonnage models presented in this paper by first testing suggested subtypes (table 1). We started with the lithotectonic classification of VMS deposits proposed by Franklin and others (2005). They subdivided the Canadian VMS deposits into five groups (1) siliciclastic-felsic in a mature epicontinental arc, (2) bimodal-felsic in an epicontinental arc, (3) bimodal-mafic in an oceanic arc, (4) mafic in a primitive oceanic backarc, and (5) pelite-mafic in a mature oceanic backarc. While classifying the deposits in our database into these five groups, we added three additional lithotectonic environments that were recognized as hosting VMS deposits in other parts of the world (1) bimodal-felsic in an oceanic arc, (2) bimodal-mafic in an epicontinental arc, and (3) mafic in a midoceanic ridge. These groups are coded for each deposit in the lithotectonic setting field in our database. The descriptions of the lithotectonic settings can be found in the Explanation of Data Fields section.

Table 1. Volcanogenic massive sulfide deposit subtypes mentioned in this paper.

Cox and Singer (1986)	Prokin and Buslaev (1999)	Franklin and others (2005)	Transitional (this paper)		Final (this paper)
Kuroko (28a)	Baimak-type	Siliciclastic-felsic in a mature epicontinental arc	Siliciclastic-felsic in a mature epicontinental arc	Felsic to intermediate	Felsic
		Bimodal-felsic in an epicontinental arc	Bimodal-felsic in an epicontinental arc	Bimodal-felsic	
			Bimodal-felsic in an oceanic arc		
	Urals-type	Bimodal-mafic in an oceanic arc	Bimodal-mafic in an oceanic arc	Bimodal-mafic	Bimodal-mafic
			Bimodal-mafic in an epicontinental arc		
Besshi (24b)	Besshi-type	Pelite-mafic in a mature oceanic backarc	Pelite-mafic in a mature oceanic backarc	Pelite-mafic	Mafic
Cyprus (24a)	Cyprus-type	Mafic in a primitive oceanic backarc	Mafic in a primitive oceanic backarc	Mafic	
			Mafic in a midoceanic ridge		

Analyses of the grades and tonnages of VMS deposits in the eight groups reveal that there are no differences among several of the tectonic groups, which could be combined as (1) the oceanic-backarc and the midoceanic-ridge groups, (2) the epicontinental-arc settings, and 3) the bimodal-rock groups in oceanic arcs. However, in mineral-resource assessments, the use of deposit models based on tectonic settings would be difficult because tectonic settings of some terranes are unknown, inconsistently classed, or controversial in paleotectonic determinations in some parts of the world.

With respect to just host lithologies of VMS deposits, three contrasting lithological groups were finally defined.

(1) **Felsic** subtype, including two groups:

(a.) Siliciclastic-Felsic—Dominantly felsic volcanic rocks (rhyolite to rhyodacite), with a continuous compositional range to basalt, and associated with abundant siliciclastic rocks (sandstone or quartzite). Dacite to andesite may be abundant. Basalt is less than 10 percent.

(b.) Bimodal-Felsic—Dominantly felsic volcanic rocks (rhyolite to rhyodacite), with andesite to basalt units constituting 10 to 50 percent. Dacite or andesite or both are rare to absent. Felsic and mafic volcanics in equal proportions are classed here.

The analysis of variance and the Tukey-Kramer HSD tests of the grades and tonnages of VMS deposits in these groups demonstrate that there is no difference between the siliciclastic-felsic and bimodal-felsic groups, so those groups are combined into a new “Felsic” grade-tonnage model.

(2) **Bimodal-Mafic** subtype of dominantly mafic volcanic rocks (andesite to basalt), with rhyolite to dacite constituting 10 to 40 percent. Dacite, andesite, or both are rare to absent.

(3) **Mafic** subtype, consisting of two groups:

(a.) Pelitic-Mafic—Dominantly mafic volcanic rocks (andesitic basalt to basalt) associated with abundant pelitic rocks. Felsic volcanic rocks constitute less than 5 percent.

(b.) Mafic—Dominantly mafic volcanic rocks (andesitic basalt to basalt) and may be associated with gabbro, diabase, and ultramafic rocks of an ophiolite sequence. Felsic volcanic rocks are rare (less than 5 percent) or absent.

There is also no significant difference between pelite-mafic and mafic groups, so those are combined into a new "Mafic" grade-tonnage model.

Host lithologies of VMS deposits are available from geologic maps or reports making their use in mineral-resource assessments more likely to be consistently useful. Generally, the use of host lithologies in a regional assessment of VMS deposits seems easier when considering the volcanic-rock sequence within five kilometers of the deposit. This distance was used to classify the deposits into subtypes.The analyses of the three grade-tonnage models are discussed in more detail in the following preliminary analyses section of this paper.

Preliminary Analysis

Grade and Tonnage Models

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 also critical to good exploration planning. In quantitative resource assessments these models play two roles (1) grade and tonnage models can help classify the known deposits in a region and aid in delineation of areas permissive for specific deposit types; and (2) the models provide information about the potential value of undiscovered deposits in the assessment area, a key to economic analyses of these resources. Construction of grade and tonnage models involves multiple steps. The first step is the identification of a group of well-explored deposits that are believed to belong to the mineral-deposit type being modeled. "Well-explored" here means completely drilled in three dimensions. 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 "Tonnage" field. We exclude deposits with grades and tonnages only in the "Comments" field because of indications that more exploration is likely for these deposits.

For each deposit type these models help define a deposit, as opposed to a mineral occurrence or a weak manifestation of an ore-forming process. The grade and tonnage models are the frequency distributions of tonnage, copper grade, zinc grade, lead grade, silver grade, and gold grade for the VMS types as represented in table 2 by their 90th, 50th, and 10th percentiles. The three subtypes of VMS deposits modeled here are felsic VMS (Felsic), bimodal-mafic VMS (Bimodal-Mafic), and mafic VMS (Mafic). Percentiles of metal grades that contain unreported values, such as Zn, Pb, Ag, and Au, were based on the observed distributions. The Shapiro-Wilk W test suggests that tonnage for the Mafic subtype is significantly different than the lognormal distribution at the one percent level, owing to the skewness caused by a few deposits with very large tonnages. Cu, Zn, and Au grades for the Felsic and Bimodal-Mafic subtypes are each significantly different than the lognormal distribution at the one percent level. In addition, Pb and Ag grades for the Felsic group are also significantly different than the lognormal distribution at the one percent level. In most cases the departures of the grades from lognormality appear to be due to some deposits that have very low grades, very high grades, or both. The reporting of very low grades may be influenced by favorable economics or technology in processing low-grade ores and may indicate regional differences that allow lower cutoff grades. Because these are at the low-grade tail of the distributions and represent a small number of deposits, they may not be important for modeling purposes. The reporting of very high grades may be due to the deposits where hand-sorting of ore was an important processing practice. Review of the literature revealed that this occurred in certain countries, such as the USA, Japan, and Spain. Because these represent a relatively small number of deposits, they have no effect on the models.

Table 2. Grade and tonnage models of felsic, bimodal-mafic, and mafic volcanogenic massive sulfide deposits.
[Tonnage is in millions of metric tons; Cu, Zn, and Pb grades are in percents; Au and Ag grades are in grams per metric ton]

VMS subtype	Tonnage and grades	Deposits (n)	10th percentile of deposits	50th percentile of deposits	90th percentile of deposits
Felsic	Tonnage	421	36.0	3.00	0.15
	Cu grade	421	3.2	1.20	0.30
	Zn grade	421	10.0	3.20	0.00
	Pb grade	421	3.2	0.42	0.00
	Au grade	421	2.6	0.40	0.00
	Ag grade	421	140.0	25.00	0.00
Bimodal-Mafic	Tonnage	272	31.0	1.90	0.14
	Cu grade	272	3.5	1.40	0.35
	Zn grade	272	8.2	1.70	0.00
	Pb grade	272	0.7	0.00	0.00
	Au grade	272	2.5	0.24	0.00
	Ag grade	272	59.0	9.50	0.00
Mafic	Tonnage	174	15.0	0.74	0.03
	Cu grade	174	4.1	1.70	0.61
	Zn grade	174	2.1	0.00	0.00
	Pb grade	174	0.0	0.00	0.00
	Au grade	174	1.7	0.00	0.00
	Ag grade	174	33.0	0.00	0.00

If there were no differences in grades or tonnages among deposit types, we could use one 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 grades or tonnages. Differences in tonnage or grades among the subtypes being tested indicate that they may be represented by different models. Analysis of variance tests of differences in mean (logarithms) tonnage, copper, zinc, lead, gold, and silver grades by type of VMS deposit reveal significant differences in copper, zinc, lead, and silver grades as expected because of how subtypes were defined. For example, the deposits associated with mafic volcanics tend to be more copper-rich, while those associated with more felsic volcanics tend to be more zinc-, lead-, and silver-rich. Gold grades showed no differences among the subtypes tested.

For construction of our models, we classified 867 deposits with grade and tonnage data into three lithologic rock groups:

1. Felsic—Dominantly felsic volcanic rocks (rhyolite to rhyodacite). In sequence of a continuous compositional range from rhyolite to basalt, dacite to andesite may be abundant and basalt is usually less than 10 percent. The volcanic rocks are associated with abundant siliciclastic rocks (sandstone or quartzite). In a felsic dominated bimodal sequence, andesite to basalt units constitute 10 to 50 percent and dacite, andesite, or both are rare to absent. Felsic and mafic volcanics in equal proportions are included here.
2. Bimodal-Mafic—Dominantly mafic volcanic rocks (andesite to basalt), with rhyolite to dacite constituting 10 to 40 percent and dacite, andesite, or both are rare to absent.
3. Mafic—Dominantly mafic volcanic rocks (andesitic basalt to basalt). Mafic volcanic rocks may be associated with gabbro, diabase, and ultramafic rocks of an ophiolite sequence. Pelitic rocks may also be abundant and dominate some sequences. Felsic volcanic rocks are rare (less than 5 percent) or absent.

The three grade and tonnage models are shown in table 2. The analysis of variance tests on the means of tonnages and grades of the three final categories demonstrate the following differences at the one percent significance level.

1. Both Felsic and Bimodal-Mafic groups are significantly larger in tonnage than the Mafic group (fig. 1).
2. The Mafic group has significantly higher copper grades than both the Felsic and Bimodal-Mafic groups (fig. 2).
3. The Felsic group has significantly higher zinc grades than the Bimodal-Mafic group, and the Bimodal-Mafic group has significantly higher zinc grades than Mafic group.
4. The Felsic group has significantly higher lead and silver grades than both the Bimodal-Mafic and Mafic groups.

These test results were consistent whether using the Tukey-Kramer HSD test, or the Kruskal-Wallis H or Wilcoxon T tests for the skewed distributions.

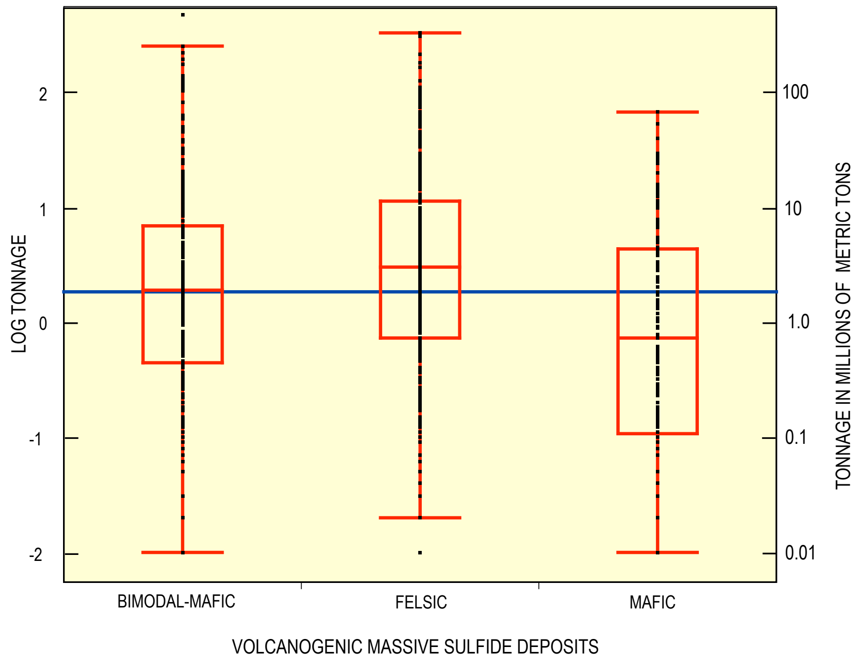

Figure 1. Box plots of deposit tonnages by volcanogenic massive sulfide deposit subtypes. Dots are deposit values. Median value is the center line of box, 25th and 75th quartiles are top and bottom of box, and the blue line is the grand mean.

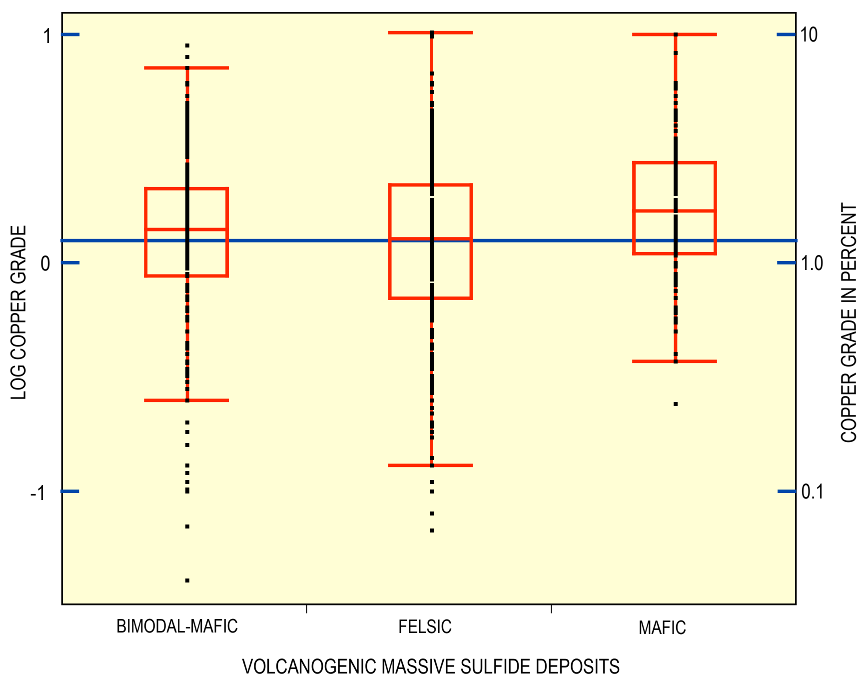

Figure 2. Box plots of average copper grades by volcanogenic massive sulfide deposit subtypes. Dots are copper grade values. Median value is the center line of box, 25th and 75th quartiles are top and bottom of box, and the blue line is the grand mean.

Frequency distributions of the tonnages and grades of copper, zinc, lead, gold, and silver in the three subtypes of VMS deposits can be used as models of the grades and tonnages of undiscovered deposits. These frequencies are plotted in figures 3–19, and the data are summarized in table 2. 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 and tonnages were based on the observed distributions.

Relationships among grade and tonnage variables are important for simulations of grades, tonnages, and estimated number of undiscovered deposits. These relationships also affect our understanding of how deposits form and our assumptions about resource availability. Correlation tests among the variables reveal the relationships of grades and tonnage. For example, a plot of average copper grade versus tonnage in each of the subtypes shows no correlation at the one percent level. Also, copper is independent of zinc, lead, and silver in each of the subtypes.

The associations of zinc, lead, and silver and of gold and silver grades are apparent regardless of the VMS subtype. Lead is strongly correlated with silver in all three subtypes ($r = 0.54$, $n = 219$ Felsic; $r = 0.76$, $n = 61$ Bimodal-Mafic; $r = 0.85$, $n = 12$ Mafic). All reported correlations are significantly different than zero at the one percent level. Zinc is strongly correlated with silver in all three subtypes ($r = 0.52$, $n = 268$ Felsic; $r = 0.57$, $n = 158$ Bimodal-Mafic; $r = 0.48$, $n = 40$ Mafic). Gold is correlated with silver in all three subtypes ($r = 0.43$, $n = 266$ Felsic; $r = 0.34$, $n = 139$ Bimodal-Mafic; $r = 0.40$, $n = 66$ Mafic).

Relationships among some grade and tonnage variables differ among VMS subtypes. For example, in the Felsic subtype, tonnage is inversely correlated at the one percent level with zinc grades ($r = –0.154$, $n = 349$), gold grades ($r = –0.17$, $n = 279$), and silver grades ($r = –0.12$, $n = 299$); zinc is strongly correlated with lead ($r = 0.60$, $n = 269$); gold is weakly correlated with copper ($r = 0.21$, $n = 277$), zinc ($r = 0.19$, $n = 244$), and lead ($r = 0.28$, $n = 195$). In the Bimodal-Mafic group, tonnage is inversely correlated with lead grades ($r = –0.42$, $n = 77$), and zinc is strongly correlated with lead ($r = 0.59$, $n = 76$). In the Mafic group, tonnage is inversely correlated with zinc grades ($r = –0.40$, $n = 57$).

The use of three VMS models in resource assessments requires us to know only the compositions of the submarine volcanics and their relative proportions. The lithologic information is available from most regional geologic maps and reports. Analyses of the grades and tonnages show that it is not necessary to interpret the paleotectonic settings for these subtypes. The implication is that it is no longer necessary to distinguish between Cyprus-type and Besshi-type deposits or the type of extensional oceanic environments they occur in, because of their similar tonnages and grades. The VMS deposits that are found in dominantly mafic or pelite-mafic volcanic environments can be represented by the Mafic grade and tonnage model.

In earlier classifications, the original kuroko-type deposit included multiple subtypes based on lithostratigraphy: siliciclastic-felsic, bimodal-felsic, and bimodal-mafic (Franklin and others, 2005). Analyses of grades and tonnages demonstrated that VMS deposits found in siliciclastic-felsic or bimodal-felsic volcanic sequences share similar grades and tonnages, and so they have been combined into one grade and tonnage model, the Felsic group. The recognition of the difference between felsic volcanic and bimodal-mafic volcanic environments is also supported by the analyses of grades and tonnages of the subtypes that occur in these settings. VMS deposits found in bimodal-mafic volcanic sequences have significantly lower zinc, lead, and silver grades than the Felsic deposits. Therefore, the deposits associated with bimodal-mafic volcanic sequences have been assigned to the Bimodal-Mafic grade and tonnage model.

In summary, the Felsic-subtype grade and tonnage model can be used to assess either permissive felsic to intermediate volcanic rocks, with or without abundant siliciclastic rocks, or dominantly felsic bimodal volcanic sequences. The Bimodal-Mafic subtype grade and tonnage model can be used to identify permissive mafic-dominated bimodal volcanic sequences. The Mafic subtype grade and tonnage model can be used to assess either dominantly mafic or pelite-mafic volcanic sequences. These grade and tonnage models can be used to estimate the grades and tonnages of undiscovered deposits found in their respective volcanic environments.

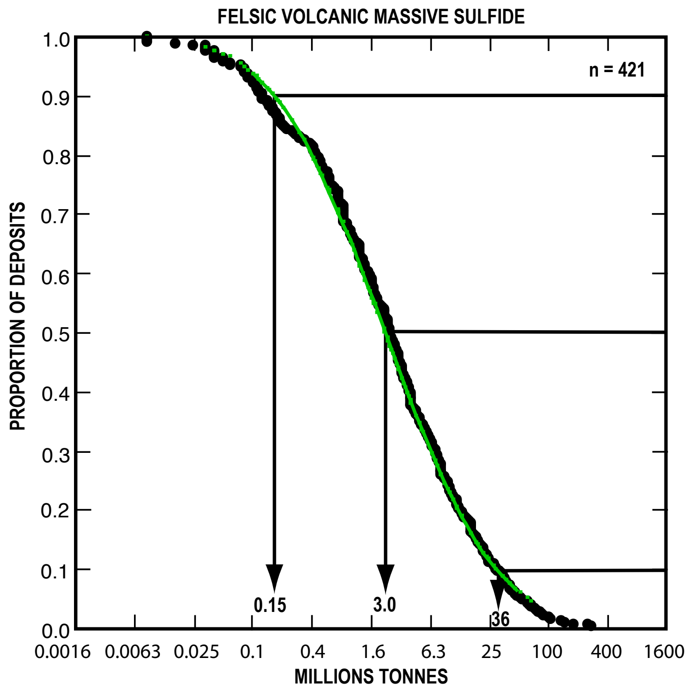

Figure 3. Cumulative frequency of ore tonnages of felsic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distribution are provided.

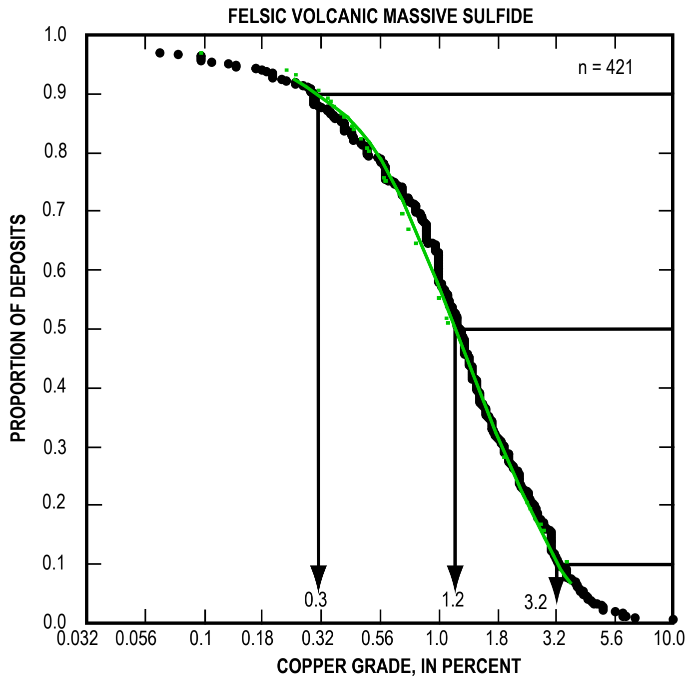

Figure 4. Cumulative frequency of copper grades of felsic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distribution are provided.

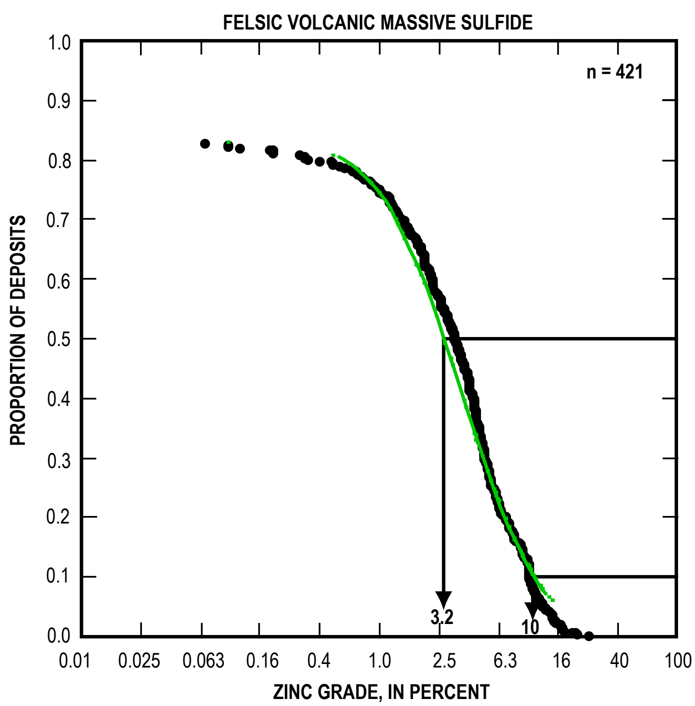

Figure 5. Cumulative frequency of zinc grades of felsic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 50th and 10th percentiles of the lognormal distribution are provided.

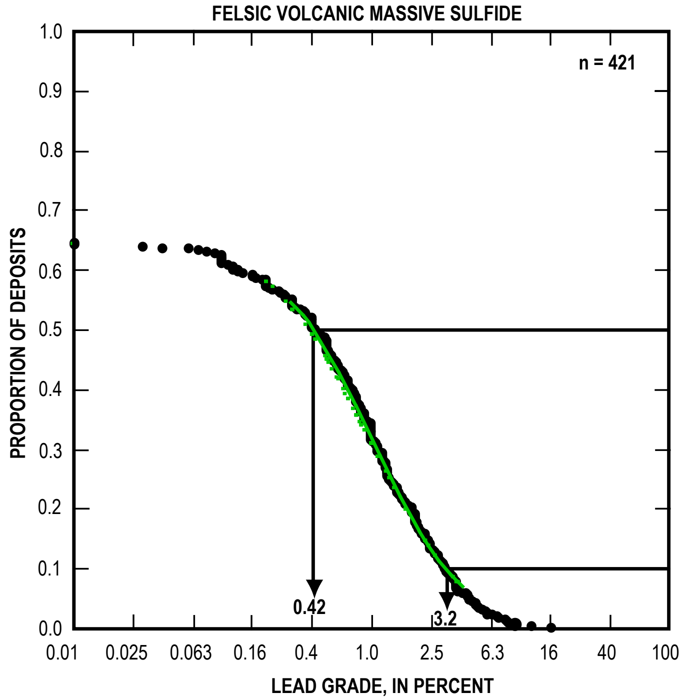

Figure 6. Cumulative frequency of lead grades of felsic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 50th and 10th percentiles of the lognormal distribution are provided.

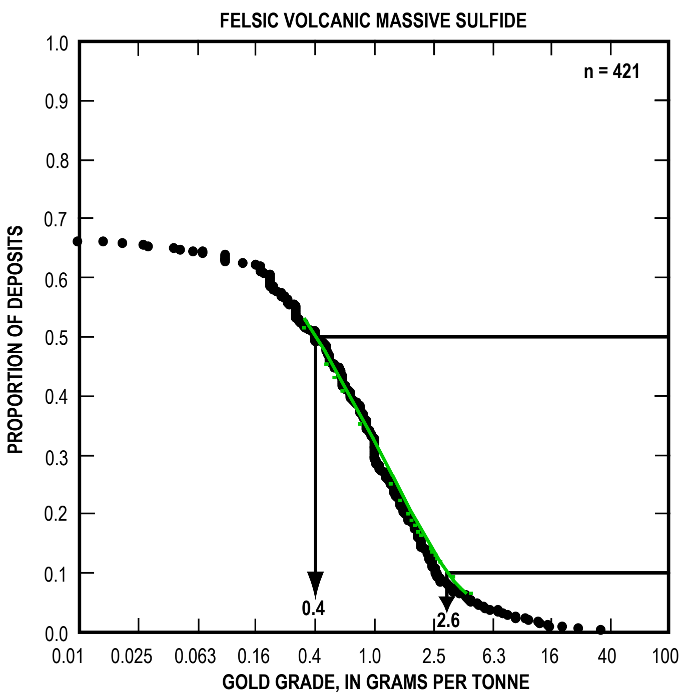

Figure 7. Cumulative frequency of gold grades of felsic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 50th and 10th percentiles of the lognormal distribution are provided.

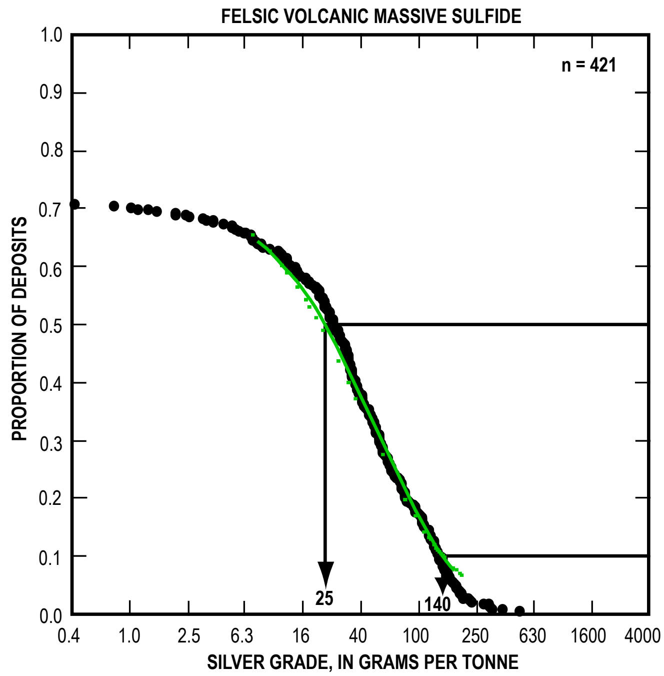

Figure 8. Cumulative frequency of silver grades of felsic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 50th and 10th percentiles of the lognormal distribution are provided.

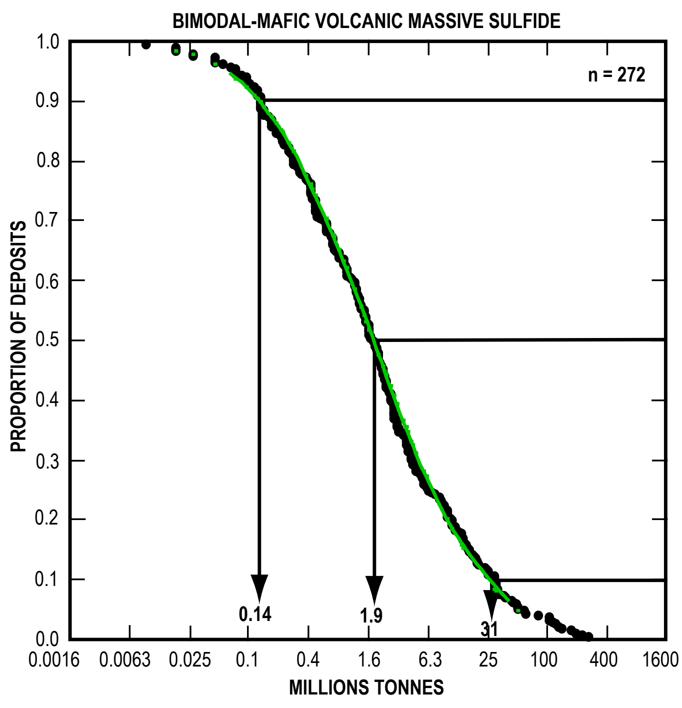

Figure 9. Cumulative frequency of ore tonnages of bimodal-mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distribution are provided.

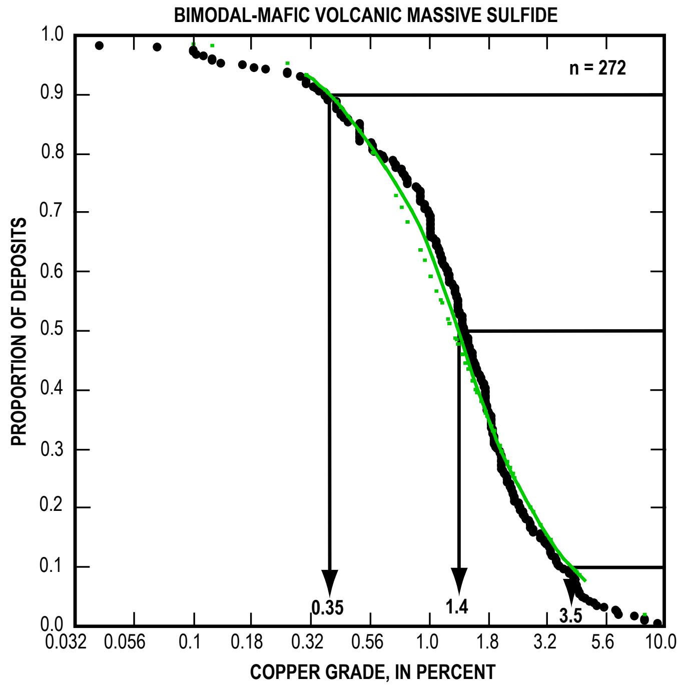

Figure 10. Cumulative frequency of copper grades of bimodal-mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distribution are provided.

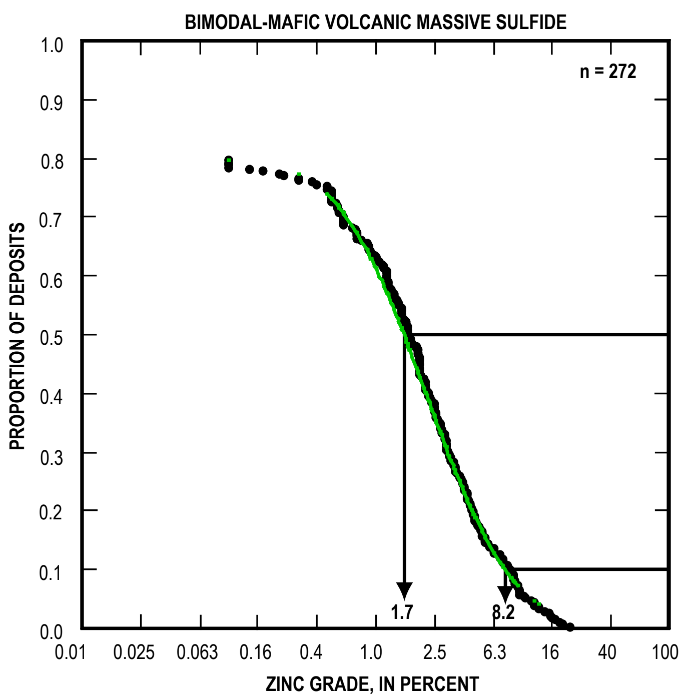

Figure 11. Cumulative frequency of zinc grades of bimodal-mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 50th and 10th percentiles of the lognormal distribution are provided.

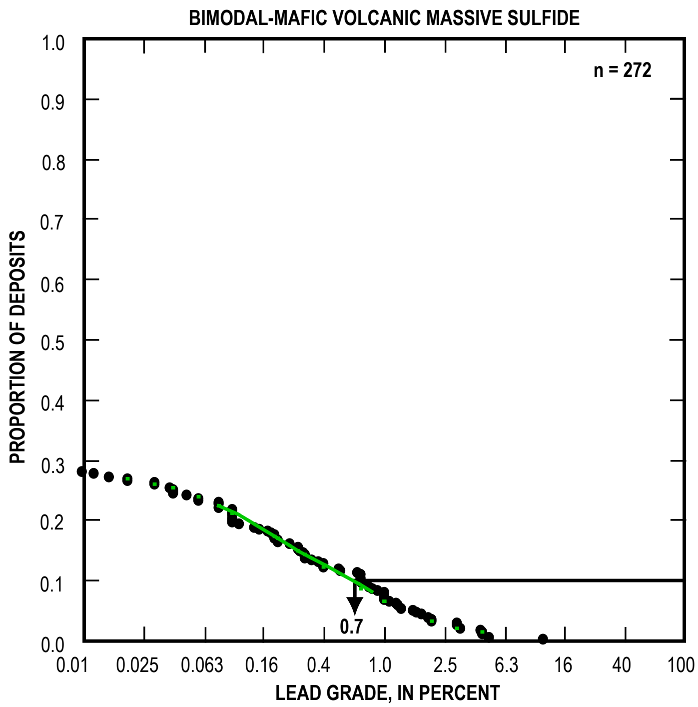

Figure 12. Cumulative frequency of lead grades of bimodal-mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercept for the 10th percentile of the lognormal distribution is provided.

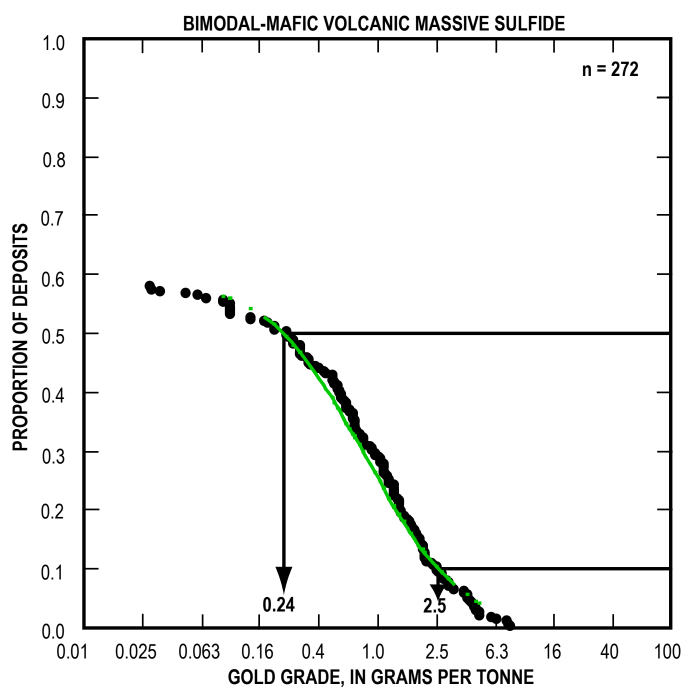

Figure 13. Cumulative frequency of gold grades of bimodal-mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 50th and 10th percentiles of the lognormal distribution are provided.

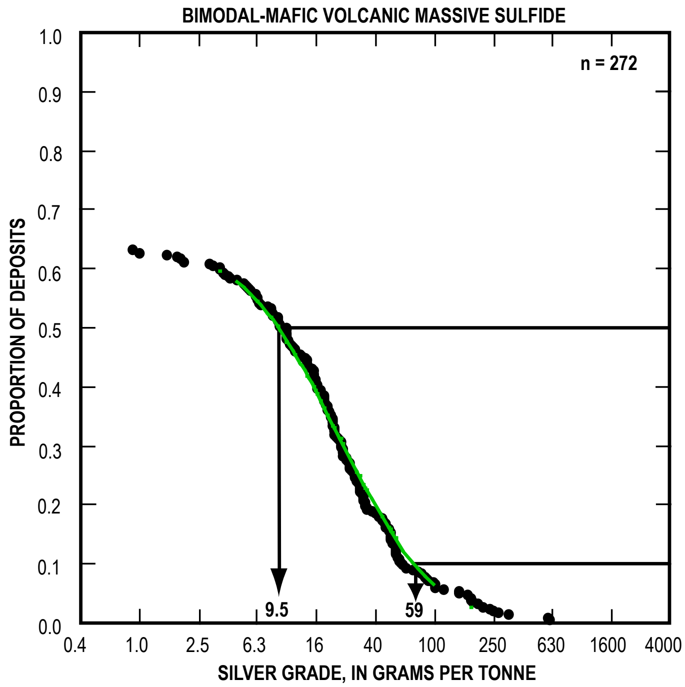

Figure 14. Cumulative frequency of silver grades of bimodal-mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 50th and 10th percentiles of the lognormal distribution are provided.

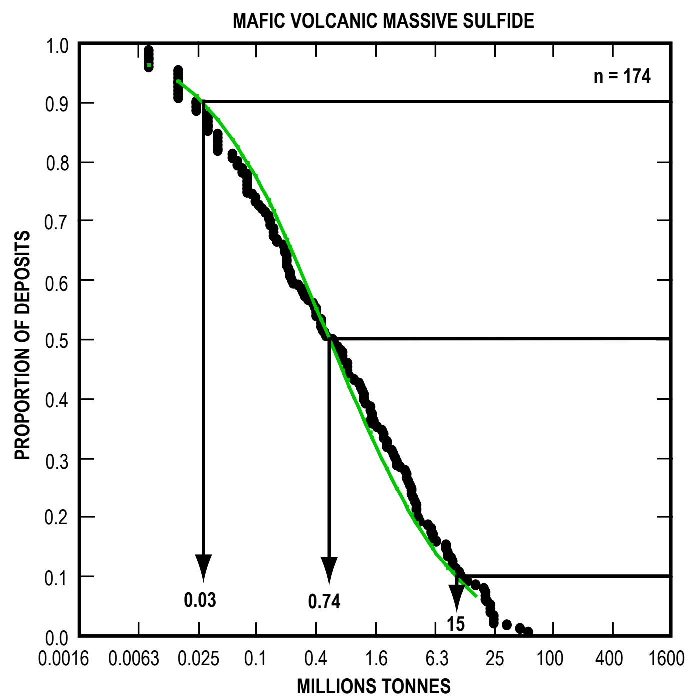

Figure 15. Cumulative frequency of ore tonnages of mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distribution are provided.

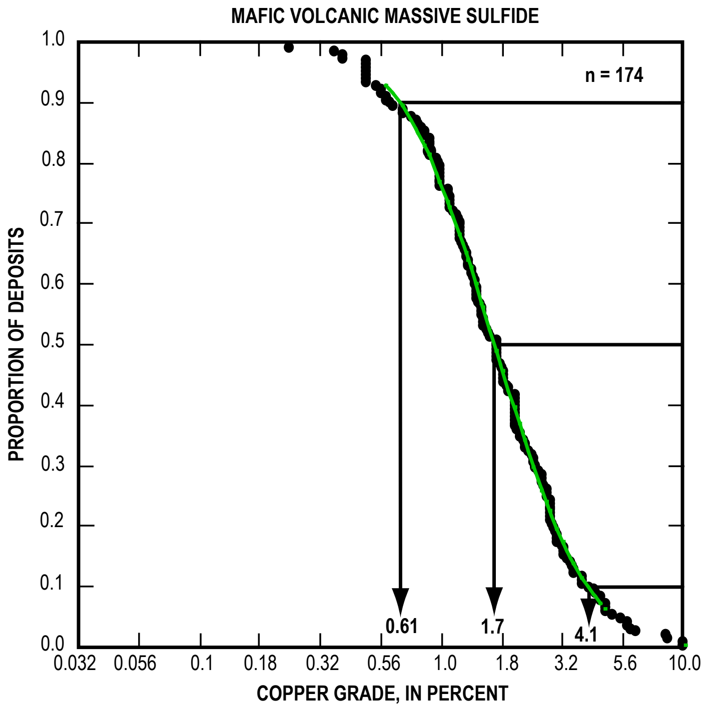

Figure 16. Cumulative frequency of copper grades of mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercepts for the 90th, 50th, and 10th percentiles of the lognormal distribution are provided.

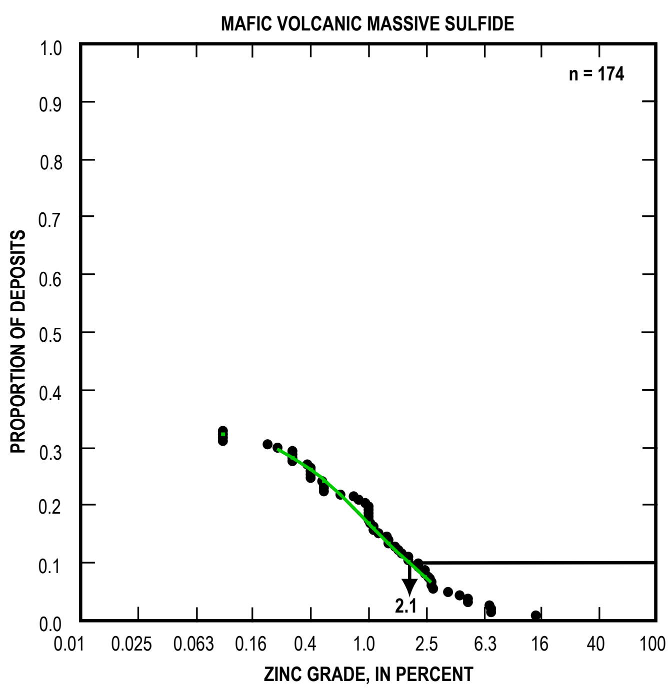

Figure 17. Cumulative frequency of zinc grades of mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercept for the 10th percentile of the lognormal distribution is provided.

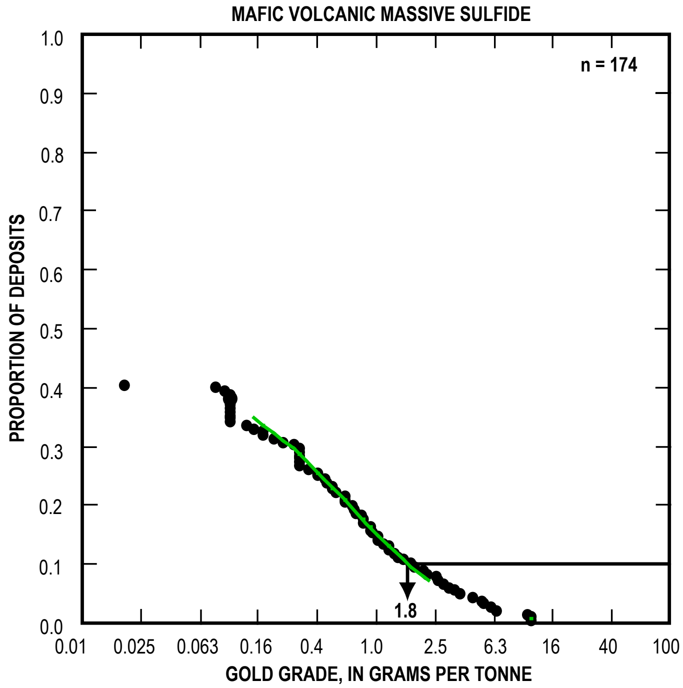

Figure 18. Cumulative frequency of gold grades of mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercept for the 10th percentile of the lognormal distribution is provided.

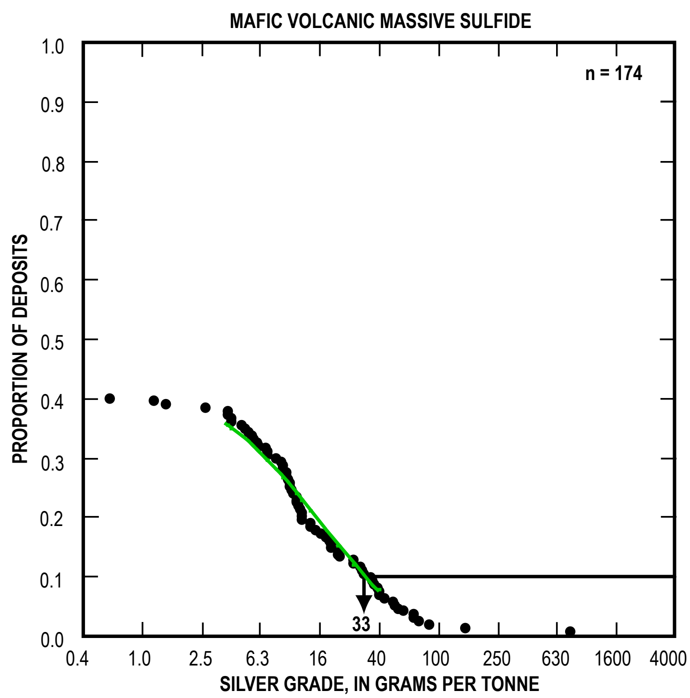

Figure 19. Cumulative frequency of silver grades of mafic volcanic massive sulfide deposits. Each dot represents an individual deposit. Intercept for the 10th percentile of the lognormal distribution is provided.

Gold-Silver and Intrusions

The behavior of gold and silver in VMS deposits is intriguing. Gold grades have no significant differences among deposits with reported gold grades in the three subtypes of VMS deposits (table 2). Out of the 866 deposits with grades and tonnages, 59 percent of them had reported gold grades. In the three VMS subtypes, average gold grades range up to 34 g/t (Dairy Farm, California) in Felsic deposits, up to 7.9 g/t (Barrett, Maine) in Bimodal-Mafic deposits, and up to 11 g/t (Skouriotissa, Cyprus) in Mafic deposits. This translates to 4,429 tonnes of gold content in the Felsic deposits, 3,646 tonnes in the Bimodal-Mafic deposits, and 481 tonnes in the Mafic deposits, thus demonstrating the importance of gold in the three VMS subtypes. Yet, it is not clear why half of the VMS deposits lack gold.

Some investigations of gold-rich VMS deposits have associated the presence of gold with igneous intrusions (Dubé and others, 2007; Hannington and others, 1999; Huston, 2000; Vikent'ev and others, 2006), although the source of the gold is uncertain.

Of 866 VMS deposits with grades and tonnages, 63 percent of them had reported silver grades. Silver is correlated with gold at the one percent confidence level in all three subtypes. The average silver grade in the Felsic VMS subtype is significantly higher than that in the Bimodal-mafic or Mafic subtypes (table 2). Among the three VMS subtypes, average silver grades range up to 500 g/t (Sierrecilla, Spain) in Felsic deposits, 603 g/t (Suriana, Mexico) in Bimodal-Mafic deposits, and 785 g/t (Samatosum, British Columbia) in Mafic deposits. There are 192,000 tonnes of silver content in the Felsic deposits, 104,000 tonnes in the Bimodal-Mafic deposits, and 16,000 tonnes in the Mafic deposits.

In our compilation, we noted the presence or absence of syn-mineral and post-mineral intrusions at each of the VMS deposits. This allowed us to test the association of the two types of intrusions, regardless of their compositions, with the presence or absence of gold and silver. The results, displayed in figures 20 and 21, are from a total of 387 deposits associated with syn-mineral intrusions and 392 deposits associated with post-mineral intrusions, respectively. Based on the Pearson Chi Square test, the association of syn-mineral intrusions with gold appears to be insignificant for the VMS deposits ($\chi^2_{0.01(2)} = 9.21$, $\chi^2 = 1.9$). However, the association of post-mineral intrusions with gold appears to be significant at the one percent level for all three subtypes ($\chi^2_{0.01(2)} = 9.21$, $\chi^2 = 12.3$).

The results displayed in figures 22 and 23 are from a total of 406 deposits associated with syn-mineral intrusions and 417 deposits associated with post-mineral intrusions, respectively. Based on the Pearson Chi Square test, the association of syn-mineral intrusions with silver appears to be insignificant for the VMS deposits ($\chi^2_{0.01(2)} = 9.21$, $\chi^2 = 3.67$). However, the association of post-mineral intrusions with silver appears to be significant at the one percent level for all three subtypes ($\chi^2_{0.01(2)} = 9.21$, $\chi^2 = 11.8$).

These results suggest the remobilization and concentration or introduction of gold and silver in VMS deposits by late intrusions. Remobilization of metals and increased gold values have been suggested at Hercules, Tasmania, Australia (Burton, 1975); Kristineberg, Sweden (Billstrom and Weihed, 1996); Currawong, Victoria, Australia (Bodon and Valenta, 1995); La Ronde-Dumagami, Quebec, Canada (Dubé and others, 2007); and the Urals deposits (Vikent'ev and others, 2006). However, some deposits with post-mineral intrusions, such as Joutel, Canada, and La Minita, Mexico, have no reported gold values. Further investigation is needed to examine if other VMS deposits have been enriched with precious metals by post-mineral intrusions.

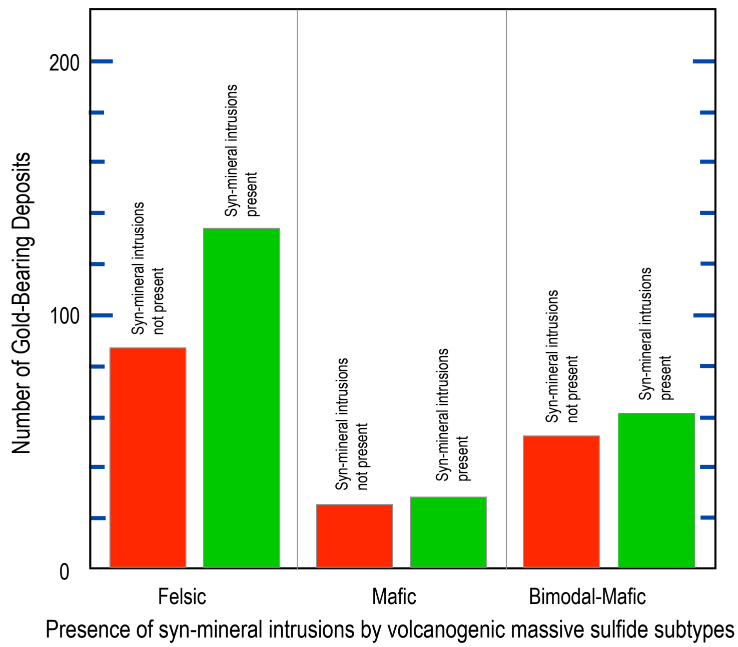

Figure 20. Comparison histograms of the presence of syn-mineral intrusions and gold-bearing volcanogenic massive sulfide subtypes (felsic, mafic, and bimodal-mafic volcanogenic massive sulfide deposits).

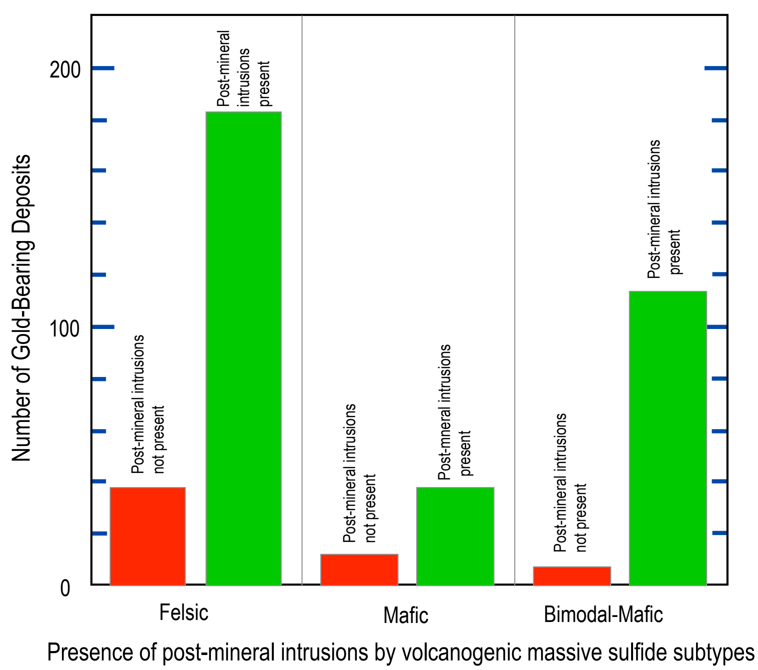

Figure 21. Comparison histograms of the presence of post-mineral intrusions and gold-bearing volcanogenic massive sulfide subtypes (felsic, mafic, and bimodal-mafic volcanogenic massive sulfide deposits).

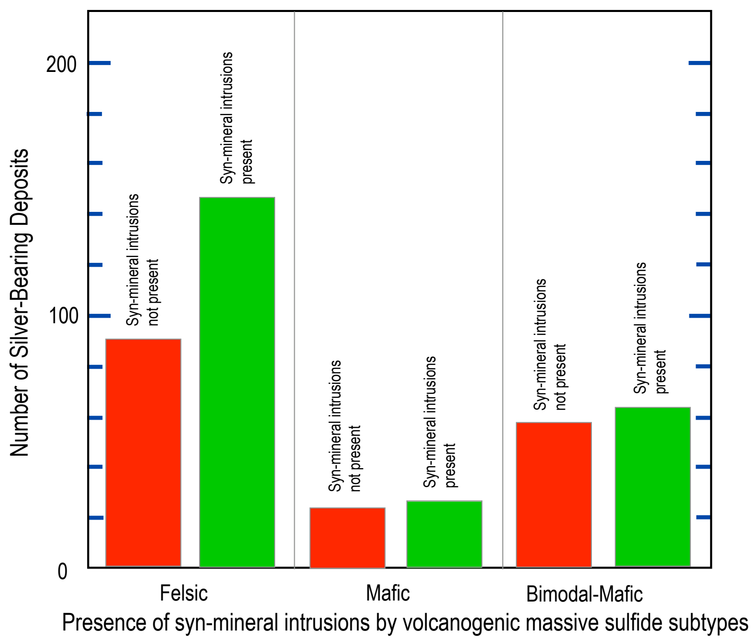

Figure 22. Comparison histograms of the presence of syn-mineral intrusions and silver-bearing volcanogenic massive sulfide subtypes (felsic, mafic, and bimodal-mafic volcanogenic massive sulfide deposits).

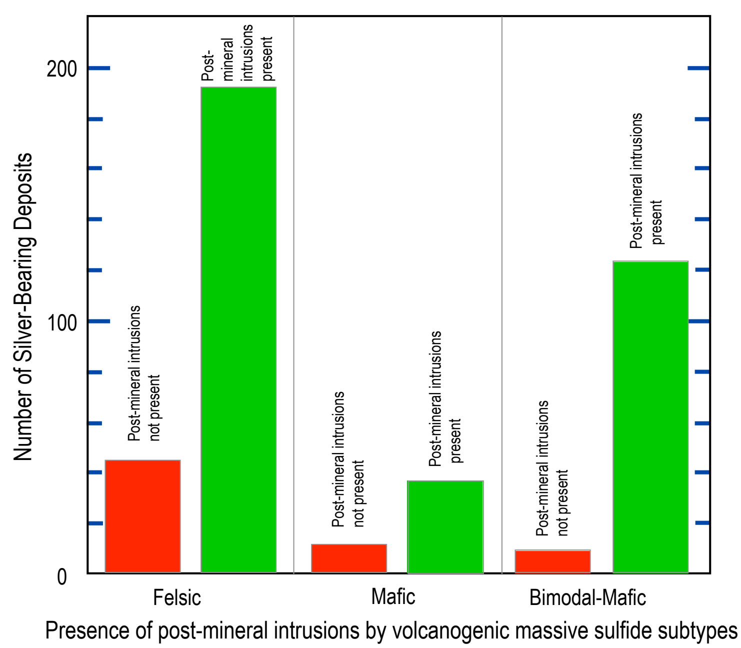

Figure 23. Comparison histograms of the presence of post-mineral intrusions and silver-bearing volcanogenic massive sulfide subtypes (felsic, mafic, and bimodal-mafic volcanogenic massive sulfide deposits).

Explanation of Data Fields

The data on the VMS deposits are contained in a FileMaker Pro 8 file “VMS.fp8”, Excel 11.3 files “VMS.xls”, “VMS-AGTN-PORT.xls”, “VMS-RUSA-VNZL.xls”, and “VMSlocations.xls”, and tab-delineated text files “VMS.tab”, “VMS-AGTN-PORT.txt”, “VMS-RUSA-VNZL.txt”, and “VMSlocations.txt”. It is recommended that the latest version of Excel is used to view the data. In addition, the file “VMS.kml” allows locations of all deposits to be plotted in GoogleEarth. The fields in the database are described below.

Deposit Name—The most recent deposit name, **“**NameDeposit”, is used. There is another field, “Other_names”, which contains alternative names that have been used for the deposit. A third field, “Includes”, provides the names of deposits that have been combined with the primary deposit as a result of the 500-meter minimum separation rule.

Location—Eleven 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 (see appendix B). Degrees, minutes, and, in some cases, seconds of longitude and latitude are provided in the 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.

Activity—Where the discovery date is know it is recorded in the “DiscoveryDate” field. If the start date of mining or production is known, it is listed in the “StartupDate” field. B.C. years are negative numbers and A.D. years are positive numbers.

Grade and Tonnage—Data gathered for each deposit include average grade of each metal of possible economic interest and the associated tonnage based on the total production, reserves, and resources at the lowest possible cutoff grade. All further references to tonnage follow this definition. All tonnages reported here (“Tonnage”) are in millions of metric tons (tonnes). Copper (“CopperGrade”), zinc (“ZincGrade”), and lead (“LeadGrade”) grades are reported as a percentage of the metals. Gold (“GoldGrade”) and silver (“SilverGrade”) grades are reported as grams/metric ton of the metal. When these grades are not available, they are treated as zero. To avoid introduction of biases into the grade and tonnage models, deposits that are known to be only partially drilled do not have their grades and tonnages reported. The “Comments” field contains supplementary information about incompletely explored deposits, as well as grades of additional elements, such as S, Ba, Pt, Pd, Cd, Se, and others when available. Three significant digits are presented for copper, zinc, lead, and gold grades, but four significant digits are used for silver grades and tonnage.

Age—In the “AgeDeposit” field, ages are presented in formal divisions of geologic time. Ages are reported in millions of years before the present (“AgeMY” field) based on reported absolute (typically zircon geothermometry or isotope geochronology) ages or midpoints of geologic time-scale units (Remane, 1998).

Mineralogy—The “Mineralogy” field contains the reported minerals listed in alphabetical order. We attempted to tabulate specific mineral names when available, but, in some cases, when specific minerals were not reported, group names were included, such as “carbonates” or “sulfosalts.” Most ubiquitous rock forming minerals, such as feldspar, calcite, and quartz, are not included. Native metals are reported with just their element names, such as gold, silver, bismuth, and platinum. For consistency, attempts were made to eliminate synonyms, such as covelline, black jack, niccolite, which were replaced by covellite, sphalerite, nickeline, respectively. Some solid solution series, such as “tennantite-tetrahedrite,” were entered as separate mineral end members of the series, such as “tennantite, tetrahedrite”. Chemical formulas were included for some unnamed species or rarer minerals. Because of the varied levels of reporting mineralogy, most of the deposits in this report display an incomplete list of minerals.

Type of Volcanogenic Massive Sulfide Deposit—The “DepositType” field is coded with our three VMS-deposit types: Felsic, Bimodal-Mafic, or Mafic. These VMS-deposit types were adopted on the basis of simplicity of use, greater relevance to map units, and our grade and tonnage models. The three VMS-deposit types are compared to previous VMS-classification schemes in table 1. The Felsic-type deposits are hosted in a dominantly felsic to intermediate volcanic sequence and includes those formerly classified as kuroko-type deposits (Singer, 1986b; Singer and Mosier, 1986b). This type includes deposits hosted in a continuous felsic to intermediate volcanic sequence, a bimodal-felsic volcanic sequence, or a siliciclastic-felsic volcanic sequence. The Bimodal-Mafic-type deposits are hosted in a dominantly mafic (andesite to basalt) volcanic sequence associated with greater than 10 percent felsic (rhyolite to rhyodacite) volcanic units. Dacite or andesite rocks are either rare or absent. This deposit type includes kuroko-type (Singer, 1986b; Singer, and Mosier, 1986b), Noranda-type (Morton and Franklin, 1987; MacGeehan and MacLean, 1980), and Urals-type (Prokin and Buslaev, 1999) deposits of previous classifications. The Mafic-type deposits are hosted in a dominantly mafic (andesitic basalt to basalt) volcanic sequence; some are associated with gabbro, diabase, and ultramafic rocks of more complete ophiolite sequences. Felsic rocks are rare or absent. This deposit type include the Cyprus-type and Besshi-type deposits (Cox, 1986; Singer, 1986a; Singer, 1986c; Singer and Mosier, 1986a). In a few cases, it was not possible to classify a deposit for lack of crucial information, such as the composition of volcanic rocks or the proportions of felsic and mafic volcanic rocks in bimodal volcanic sequences.

Size and Shape of Deposit—To consistently capture information about the size and shape of deposits, alteration zones, geochemical anomalies, and geophysical anomalies in two-dimensional projections to the surface, we use the rigorous procedures used by Griffiths (1967) for mineral-grain images. The shortest dimension (b axis) is measured as the distance between parallel lines that just touch the object. After the short dimension is determined, the long axis is measured perpendicular to the b axis using the same criteria. Alteration, ore, and sulfide zones can be well represented by an ellipse. Where published estimates of the projected area of the body are not available we estimated the area using the standard formula for area of an ellipse (area = 3.14159 a b / 4). If, however, massive sulfide bodies have concave sides, the assumption of an elliptical shape will result in an over estimate of the area. For example, the Stekenjokk deposit in Sweden has a markedly concave shape and a measured area that is less than a third of that calculated by assuming an ellipse shape. In these cases, we used the measured area. The area of the deposit in square kilometers is in the “AreaDeposit” field, the major axis of the deposit is in “AaxisDeposit” field, and the minor axis in “BaxisDeposit” field. The “AreaAlteration” field represents the area of alteration in square kilometers; the “BaxisAlter” field represents the alteration minor axis in kilometers, and the “AaxisAlter” field represents the alteration major axis in kilometers. The element geochemical anomaly, element geochemical anomaly major axis, and element geochemical anomaly minor axis are represented by the fields “ElementGeochemAnomaly”, “AaxisGeochem”, “BaxisGeochem”, respectively. Similarly, the geophysics anomaly, major axis, and minor axis are represented by the fields “GeophysicsAnomaly”, “AaxisGeophyAnomaly”, and BaxisGeophyAnomaly”, respectively.

Deposit Cover—The “Cover_in_m” field provides information about the thickness of the covering material. A zero value indicates that the ore deposit, including gossan outcrops, is exposed at the surface. A value greater than zero depicts the thickness of the material covering the deposit. Deposit cover values may also include the water depth for deposits hidden beneath a lake, such as at Chisel Lake, Manitoba, Canada. No value indicates that no information is available for this field.

Spatially Associated Rocks—Rocks in and around the VMS deposit are recorded in the same terms used in the published maps and reports. The "Host_rocks" field is used for rocks that are in direct contact with the ore deposit. The "Rocks_overlying_ore" field is used for rocks that stratigraphically overlie the ore deposit. When available, we list the stratigraphic order of rock units from top to bottom, with given or measured thicknesses of rock units shown in parentheses. The "Rocks_underlying_ore" field is used for rocks that stratigraphically underlie the ore deposit. When available, we list the stratigraphic order of rock units from top to bottom, with given or measured thicknesses of rock units shown in parentheses. In all three fields, facies associations in the same horizon are indicated by rock names connected by hyphens. The rocks listed are those that occur in the stratigraphic column immediately around the VMS deposit. Some rocks that are important in exploration for VMS deposits, such as exhalite beds (for example, chert, jasperoid, or siliceous bed), may not have been recorded if they were not recognized by the investigators. Rocks on a regional map found within 5 kilometers of the deposit are in the "RocksWithin5km" field. When available, the ages of the associated rocks are added to the field.

Spatially Related Deposits—The "DepositTypesWithin5km" field contains deposit types that are within 5 kilometers of a VMS deposit. The "DepositsTypesWithin10km" field contains deposit types that are within 10 kilometers of a VMS deposit. In many situations, these spatially related deposits are merely occurrences and not economic mineral deposits. The deposit type is designated using the model number and name listed in USGS Bulletins 1693 (Cox and Singer, 1986) and 2004 (Bliss, 1992).

Lithotectonic Setting—In the "Lithotectonic_setting" field, we have subdivided the deposits among eight lithostratigraphic associations in tectonic settings. When the lithotectonic setting was undetermined, it was coded as "Unclassified". The lithotectonic settings are defined as follows:

1. Siliciclastic-felsic in a mature epicontinental arc. Found in epicontinental backarc settings, the stratigraphy consists of continent-derived sedimentary rocks (~80%) and felsic volcaniclastic rocks, with minor flows domes, and their intrusive equivalents (~25%), mafic (tholeiitic to alkaline) flows, sills, and minor volcaniclastic rocks (~10%). Mafic volcanic rocks and argillaceous and chemical sedimentary rocks are typically in the hanging wall.

2. Bimodal-felsic in an epicontinental arc. Found in rifted continental margins and incipient (suprasubduction related) arcs, the stratigraphy consists of submarine felsic volcanic rocks (35-70%), basalt (20-50%), and terrigenous sedimentary strata (~10%).

3. Bimodal-felsic in an oceanic arc. Found in oceanic backarc rifts, the stratigraphy consists of submarine felsic volcanic rocks (50-70%), mafic volcanic rocks (20-50%), and sedimentary rocks (up to 30%).

4. Bimodal-mafic in an epicontinental arc. Found in epicontinental backarc settings, the stratigraphy is dominated by mafic volcanic rocks (pillowed and massive basaltic flows and pyroclastic rocks), with minor felsic volcanic rocks (flows, pyroclastic rocks, domes) and volcaniclastic rocks (<25%), and subordinate terrigenous sedimentary rocks.

5. Bimodal-mafic in an oceanic arc. Found in incipient-rifted arcs above intraoceanic subduction zones. The stratigraphy is dominated by basalt pillowed and massive flows and volcaniclastic rocks with minor felsic flows, volcaniclastic rocks, and domes (<25%), and subordinate terrigenous sedimentary rocks.

6. Mafic in a primitive oceanic backarc. This stratigraphy includes mature intraoceanic backarcs and transform fault settings, dominated by MORB-boninitic and tholeiitic successions of pillowed and massive basalt flows, minor felsic flows and domes, including subvolcanic plagiogranite and icelandite,

minor ultramafic flows and intrusions, synvolcanic mafic dikes and sills (up to 50%), and prominent altered mafic synvolcanic intrusions. Sedimentary rocks are minor (<10). Less common is alkaline basalt (locally bimodal) in oceanic island or late-stage continental backarc seamount environments.

7. Mafic in a midoceanic ridge. The stratigraphy consists of dominantly massive and pillowed basalt flows associated with synvolcanic mafic dikes or sills, ultramafic flows, and intrusions, typically part of an ophiolite sequence. Felsic volcanic and sedimentary rocks are rare (<5%). This mafic setting is distinguished from the primitive oceanic backarc setting by the absence of an associated arc.

8. Pelite-mafic in a mature oceanic backarc. This stratigraphy includes mature oceanic backarc and sediment-covered midoceanic ridge and transform fault settings. The stratigraphy consists of basalt and pelite, in equal proportions, to pelite-dominated successions, with mafic sills (up to 25%), felsic flows, sills, domes, and volcaniclastics (<5% or absent), and carbonaceous argillite with subordinate siltstone, wacke, and sandstone.

Because of the difficulty of recognizing the specific lithotectonic setting for each of the VMS deposits in this report, the lithotectonic setting classification should be viewed as preliminary. Many of the volcanic belts have not been sufficiently investigated to determine whether they were formed in an epicontinental (sialic) or an oceanic (ensimatic) environment. Furthermore, the tectonic settings of some belts are not in agreement among investigators, such as at Joma, Norway (Stephens and others, 1984). Lithogeochemical data, particularly for the rare earth elements, are not available for many volcanic rocks that would allow classification of paleotectonic environments using element-ratio discriminant diagrams.

Metamorphism, Deformation, and Intrusions—Information about metamorphism, deformation, and intrusions is entered in four fields. The fields "PostMineral_deformation?", "SynMineral_intrusion?", and "PostMineral_intrusion?" indicate the presence of deformation with a "yes" or "no". Post-mineral deformation includes such actions on the ore deposit as folding, displacement, and shearing. The presence of subvolcanic or plutonic intrusive bodies that were emplaced at the time of mineralization, or after mineralization, is indicated in the "SynMineral_intrusion?" and "PostMineral_intrusion?" fields, respectively. The grade of regional metamorphism and, where intrusions are present, the nature of contact-hydrothermal effects, are shown in the "Metamorphic_grade" field. In some cases, diagnostic metamorphic minerals and contact temperature and pressure are given.

Syndeposition Controls—The structural controls of the mineralization are shown in the field "Syndeposition_controls". The term "stratigraphic" is used to describe stratabound or stratiform deposits that occur mostly within a single lithostratigraphic unit. "Rock contact" is used to describe ore deposits that occur either at the contact between two different rock layers or with a discordant rock body, such as a dome or an intrusion. Other terms in this field are recorded as initially reported.

Sources—Papers, web sites, and unpublished sources that provided data for each deposit are listed in the field "References".

Location Map

Figure 24 displays a world map showing the distribution of the three subtypes of VMS deposits from our database.

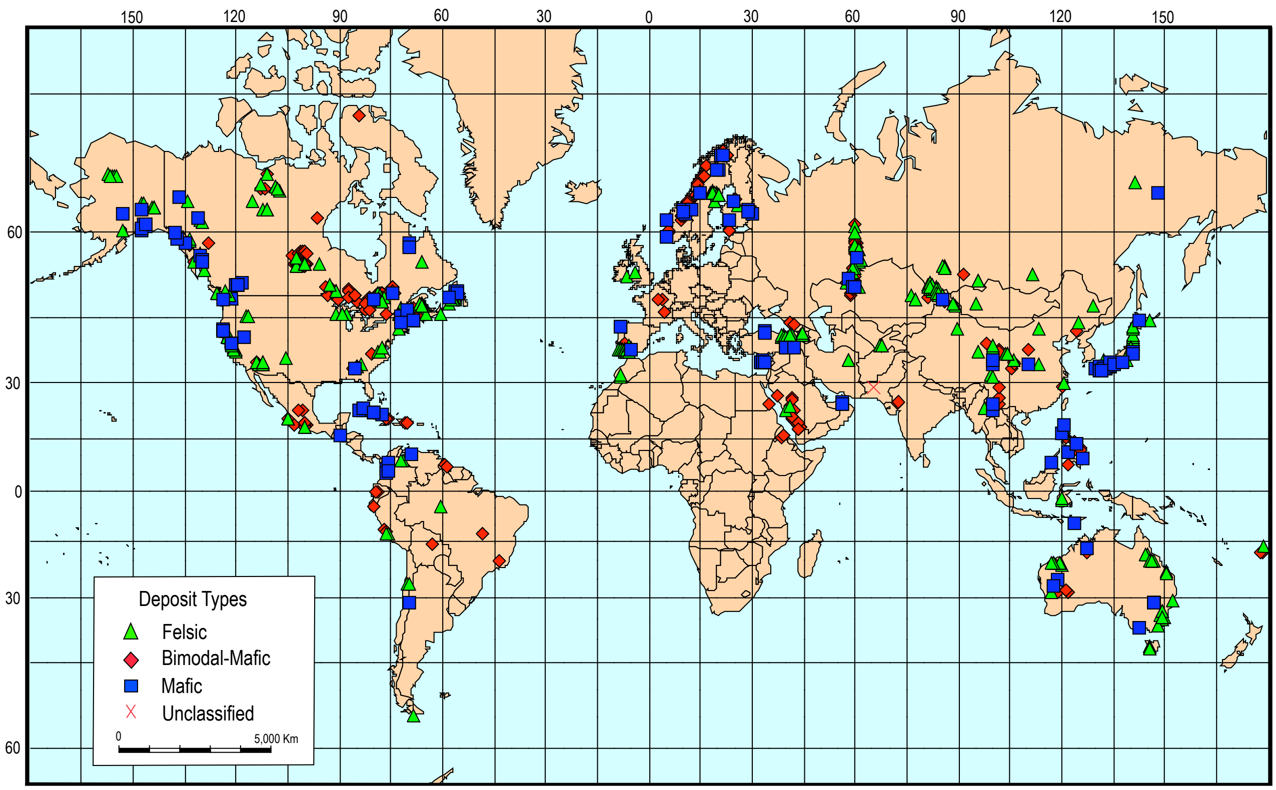

Figure 24. World map showing the distribution of volcanogenic massive sulfide deposit subtypes.

Acknowledgments

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Appendixes

A. Summary Statistics For Volcanogenic Massive Sulfide Grade-Tonnage Models

Summary statistics for the three subtypes of VMS are presented below. The ranges, percentages, and statistics given for each are computed from selected database fields. Deposits added to the database after the analyses and not included in the statistics below are Amjabi and Deri, India; Donggouba and Meixian, China; and Elizabeth, Island Mountain, and Holden, USA. Abbreviations: km, kilometers; Ma, million years; g/t, grams per tonne.

Felsic Volcanogenic Massive Sulfide Deposits

Tonnage—

Median 3 million tonnes (421 deposits).
90th percentile 0.15 million tonnes.
10th percentile 36 million tonnes.

Grades—

Copper:
Median 1.2% Cu (411 deposits).
90th percentile 0.3% Cu.
10th percentile 3.2% Cu.

Zinc:
Median 3.2% Zn (348 deposits).
10th percentile 10% Zn.

Lead:
Median 0.42% Pb (271 deposits).
10th percentile 3.2% Pb.

Gold:
Median 0.4 g/t Au (278 deposits).
10th percentile 2.6 g/t Au.

Silver:
Median 25 g/t Ag (298 deposits).
10th percentile 140 g/t Ag.

*Age—*Range for 529 deposits: 5 Ma (Pliocene) to 3,500 Ma (Archean), mean 699 Ma, median 390 Ma. Period or epoch names of ages of the ores are listed with the percentage of the 529 deposits.

Devonian, 24%
Proterozoic, 13%
Ordovician, 12%
Cambrian, 10%
Archean, 8%
Carboniferous, 7%
Miocene-Pliocene, 7%
Cretaceous, 6%
Triassic-Jurassic, 6%
Silurian, 4%
Permian, 2%
Eocene, 1%

Area of Deposit—0.00005 to 3.2 km^2, median 0.02 km^2 (71 deposits).

Deposit A Axis—0.0254 to 6 km (256 deposits).

Deposit B axis—0.001 to 2.2 km (245 deposits).

Alteration Area—0.09 to 24.5 km^2, median 3.2 km^2 (9 deposits).

Alteration A Axis—0.12 to 30 km (41 deposits).

Alteration B Axis—0.025 to 3.5 (42 deposits).

Stringer Zone—Of 529 felsic deposits, an underlying stringer zone occurs beneath 205 deposits and is not present in 192 deposits. No information about stringer zones was available for 132 deposits.

Syndepositional Controls—In 529 felsic deposits, the types of syndepositional controls include stratigraphic (54%), open-space matrix fillings (23%), rock contact (16%), and depressions (6%). No information about controls was available for 22 percent of the deposits.

Host Rocks—Names of rocks in the horizon directly in contact with the ore deposit are listed with the percentage (to five percent) of the 529 deposits. For example, rhyolite tuff occurs in the 43 percent of 529 felsic deposits. Some rocks have been combined, such as sandstone and conglomerate, and are displayed with hyphens.

rhyolite tuff, 43%
rhyolite flows, 31%
shale-mudstone, 29%
sandstone-conglomerate, 23%
dacite flows, 12%
andesite flows, 11%
chert-exhalites-iron formation, 11%
dacite tuff, 9%
limestone-dolomite, 9%
rhyolite subvolcanic intrusions, 8%

rhyolite breccia, 7%
rhyodacite flows, 6%
andesite tuff, 5%
basalt flows, 5%

Overlying Rocks—Names of rocks from two stratigraphic horizons lying above the ore deposit are listed as follows.

Overlying Rock 2
Overlying Rock 1
Ore deposit

Percentages (to five percent) of the presence of rocks in 529 deposits are shown. For example, rhyolite tuff occurs in the horizon (Overlying Rock 1) immediately overlying the deposit in 16 percent of 529 felsic deposits.

Overlying Rock 2—No data (44%), rhyolite tuff (8%), shale (5%)

Overlying Rock 1—No data (21%), rhyolite tuff (16%), chert-exhalites-iron formation (9%), shale (5%)

Underlying Rocks—Names of rocks from two stratigraphic horizons lying beneath the ore deposit are listed as follows.

Ore deposit
Underlying Rock 1
Underlying Rock 2

Percentages (to five percent) of the occurrence of rocks in 529 deposits are shown. For example, rhyolite tuff occurs in the horizon (Underlying Rock 1) immediately underlying the deposit in 16 percent of 529 felsic deposits.

Underlying Rock 1—No data (24%), rhyolite tuff (16%), rhyolite flows (9%), dacite tuff (5%), andesite flows (5%)

Underlying Rock 2—No data (48%), andesite flows (6%), rhyolite tuff (6%), rhyolite flows (6%)

Rocks within 5 km—Names of rocks from regional geologic maps that occur within 5 km of felsic VMS deposits are listed with associated percentages (to five percent) in 529 deposits. For example, felsic flows occur within 5 km of 71 percent of 529 felsic deposits. There are no data for six percent of the deposits.

felsic flows or breccia, 71%
pelites, 63%
mafic flows or breccia, 61%

clastics, 57%
felsic pyroclastics or volcaniclastics, 57%
intermediate flows or breccia, 52%
felsic intrusions, 52%
intermediate intrusions, 46%
carbonates, 40%
mafic intrusions, 32%
intermediate pyroclastics or volcaniclastics, 30%
chert or iron formation, 20%
mafic pyroclastics or volcaniclastics, 20%
ultramafic intrusions, 16%
surficial sediments, 14%
undifferentiated sedimentary rocks, 9%

Minerals—Minerals reported in felsic VMS deposits are listed. Common minerals, such as quartz, feldspar, and calcite, are excluded. Percentages (to five percent) of the presence of minerals in 529 deposits are shown. For example, pyrite occurs in 94 percent of 529 felsic deposits. There are no data for four percent of the deposits:

pyrite, 94%
chalcopyrite, 92%
sphalerite, 88%
galena, 78%
chlorite, 54%
sericite, 51%
pyrrhotite, 43%
tetrahedrite, 41%
barite, 40%
tennantite, 33%
arsenopyrite, 34%
magnetite, 33%
bornite, 27%
chalcocite, 21%
hematite, 21%
covellite, 20%
gold, 19%
marcasite, 18%
electrum, 15%
silver, 14%
epidote, 12%
carbonate, 12%

rutile, 11%
gypsum, 10%
bournonite, 10%
malachite, 9%
enargite, 9%
argentite, 9%
bismuthinite, 9%
fluorite, 9%
bismuth, 9%
dolomite, 8%
hessite, 8%
azurite, 8%
muscovite, 8%
biotite, 8%
ilmenite, 7%
talc, 7%
cassiterite, 7%
siderite, 7%
kaolinite, 7%
cubanite, 7%
boulangerite, 7%),
molybdenite, 7%
stannite, 7%
garnet, 6%
copper, 5%
ankerite, 5%
altaite, 5%
actinolite, 5%
stromeyerite, 5%
pyrargyrite, 5%
cuprite, 5%
tetradymite, 5%
apatite, 5%

Metamorphic Grade—Presence of metamorphic grades is listed with associated percentages (to 5 percent) in 529 felsic deposits. For example, the greenschist metamorphic grade occurs in 37 percent of 529 felsic deposits. No information about metamorphic grade was available for 21 percent of the deposits.

greenschist, 37%
lower greenschist, 19%

Deposit Types within 5 km—Deposit types that occur within 5 km of felsic VMS deposits are listed with associated percentages (to five percent) in 529 deposits. For example, 28a (kuroko vms) deposits occur within 5 km of 59 percent of 529 felsic deposits. There are no data for 15 percent of the deposits.

28a (kuroko vms), 59%
none, 17%
24c (volcanogenic Mn), 10%
36a (low-sulfide Au quartz veins), 5%

Deposit Types within 10 km—Deposit types that occur within 10 km of felsic VMS deposits are listed with associated percentages (to five percent) in 529 deposits. For example, 28a (kuroko vms) deposits occur within 10 km of 64 percent of 529 felsic deposits. There are no data for 18 percent of the deposits.

28a (kuroko vms), 64%
24c (volcanogenic Mn), 12%
none, 10%
27d (simple Sb), 6%
36a (low-sulfide Au-quartz vein), 5%

Post-Mineral Deformation—In 529 felsic deposits, post-mineral deformation occurs in 80 percent of the deposits and do not occur in 5 percent of the deposits. There are no data for 15 percent of the deposits.

Syn-Mineral Intrusion—In 529 felsic deposits, syn-mineral intrusions occur in 49 percent of the deposits and do not occur in 27% of the deposits. There are no data for 24 percent of the deposits.

Post-Mineral Intrusion—In 529 felsic deposits, post-mineral intrusions occur in 65 percent of the deposits and do not occur in 14 percent of the deposits. There are no data for 21 percent of the deposits.

Lithotectonic Setting—Felsic deposits (529) are associated with siliciclastic-felsic rocks in mature epicontinental arcs (52%), bimodal-felsic rocks in epicontinental arcs (36%), and bimodal-felsic rocks in oceanic arcs (12%).

Bimodal-Mafic Volcanogenic Massive Sulfide Deposits

Tonnage—

Median: 1.9 million tonnes (272 deposits).
90th percentile: 0.14 million tonnes.
10th percentile: 31 million tonnes.

Grades—

Copper:
Median: 1.4% Cu (267 deposits).
90th percentile: 0.35% Cu.
10th percentile: 3.5% Cu.

Zinc:
Median: 1.7% Zn (217 deposits).
10th percentile: 8.2% Zn.

Lead:
10th percentile: 0.7% Pb (77 deposits).

Gold:
Median: 0.24 g/t Au (158 deposits).
10th percentile: 2.5 g/t Au.

Silver:
Median: 9.5 g/t Ag (172 deposits).
10th percentile: 59 g/t.

Age—Range for 354 deposits—15 Ma (Miocene) to 3,200 Ma (Archean), mean 1,384 Ma, median 1,500 Ma. Period or epoch names of ages of the ore are listed with the percentage of the 354 deposits.

Proterozoic, 31%
Archean, 28%
Ordovician, 13%
Devonian, 8%
Silurian, 6%
Cretaceous, 4%
Cambrian, 3%
Paleocene-Eocene, 3%
Triassic-Jurassic, 1%
Oligocene-Miocene, 1%
Permian, 1%

Area of Deposit—0.0004 to 0.95 km^2, median 0.03 km^2 (33 deposits).

Deposit A Axis—0.015 to 8 km (156 deposits).

Deposit B Axis—0.001 to 3 km (145 deposits).

Alteration Area—0.87 to 9.4 km^2, median 2.85 km^2 (2 deposits).

Alteration A Axis—0.09 to 6 km (18 deposits).

Alteration B Axis—0.03 to 2 km (15 deposits).

Stringer Zone—Of 354 bimodal-mafic deposits, an underlying stringer zone occurs beneath 115 deposits and was not identified in 156 deposits. No information about stringer zones was available for 82 deposits.

Syndepositional Controls—In 354 bimodal-mafic deposits, the types of syndepositional controls include stratigraphic (59%) and rock contact (15%). No information about controls was available for 21 percent of the deposits.

Host Rocks—Names of rocks in the ore horizon directly in contact with the ore deposit are listed with the percentage (to five percent) of the 354 deposits.

rhyolite tuff, 29%
rhyolite flows, 24%
basalt flows, 23%
andesite flows, 22%
volcaniclastics, 12%
dacite flows, 11%
chert-exhalites-iron formation, 10%
shale-mudstone, 10%
sandstone-conglomerate, 7%
andesite tuff, 7%
dacite tuff, 7%
limestone-dolomite, 7%
rhyolite breccia, 6%
rhyodacite subvolcanic intrusions, 5%

Overlying Rocks—Names of rocks reported from two stratigraphic horizons lying above the ore deposit are listed as follows.

Overlying Rock 2
Overlying Rock 1
Ore deposit

Percentages (to five percent) of the presence of rocks in 354 deposits are as follows.

Overlying Rock 2—No data (49%), basalt flows (10%), rhyolite flows (7%), andesite flows (7%)

Overlying Rock 1—No data (19%), rhyolite tuff (16%), andesite flows (12%), basalt flows (8%), chert-exhalites-iron formation (7%), rhyolite flows (5%), andesite tuff (5%), basalt tuff (5%)

Underlying Rocks—Names of rocks reported from two stratigraphic horizons lying beneath the ore deposit are listed as follows.

Ore deposit
Underlying Rock 1
Underlying Rock 2

Percentages (to five percent) of the presence of rocks in 354 deposits are as follows.

Underlying Rock 1—No data (19%), rhyolite tuff (17%), rhyolite flows (13%), basalt flows (12%), andesite flows (8%)

Underlying Rock 2—No data (47%), basalt flows (9%), rhyolite flows (9%), andesite flows (8%)

Rocks within 5 km—Names of rocks from regional geologic maps that occur within 5 km of bimodal-mafic VMS deposits are listed with associated percentages (to five percent) in 354 deposits. There are no data for 11 percent of the deposits.

mafic flows or breccia, 78%
mafic pyroclastics or volcaniclastics, 62%
felsic intrusions, 55%
felsic flows or breccia, 51%
clastics, 51%
intermediate flows or breccias, 49%
intermediate intrusions, 47%
mafic intrusions, 47%
felsic pyroclastics or volcaniclastics, 45%
pelites, 40%
intermediate pyroclastics or volcaniclastics, 39%
undifferentiated sedimentary rocks, 32%
ultramafic intrusions, 30%
carbonates, 27%
chert or iron formation, 24%
Quaternary sediments, 15%
carbonatite, 12%

Minerals—Minerals reported in bimodal-mafic VMS deposits are listed. Common minerals, such as quartz, feldspar, and calcite, are excluded. Percentages (to five percent) of the presence of minerals in 354 deposits are shown. There are no data for 4 percent of the deposits.

chalcopyrite, 94%
pyrite, 90%
sphalerite, 85%
pyrrhotite, 61%
galena, 51%

chlorite, 49%
sericite, 37%
magnetite, 37%
arsenopyrite, 22%
tetrahedrite, 19%
bornite, 16%
gold, 15%
barite, 15%
epidote, 14%
biotite, 14%
marcasite, 14%
hematite, 14%
carbonate, 13%
tennantite, 12%
chalcocite, 11%
cubanite, 11%
muscovite, 10%
molybdenite, 10%
silver, 10%
ilmenite, 9%
actinolite, 9%
covellite, 9%
rutile, 8%
mackinawite, 7%
malachite, 7%
anhydrite, 6%
hessite, 6%
garnet, 6%
valleriite, 6%
talc, 6%
electrum, 6%
tremolite, 5%
hornblende, 5%
anthophyllite, 5%
gypsum, 5%
cordierite, 5%
dolomite, 5%
bournonite, 5%
azurite, 5%

Metamorphic Grade—Presence of metamorphic grades is listed with associated percentages (to five percent) in 354 bimodal-mafic deposits. No information about metamorphic grade was available for 29 percent of the deposits.

greenschist, 37%
amphibolite, 9%
lower greenschist, 8%

Deposit Types within 5 km—Deposit types that occur within 5 km of bimodal-mafic VMS deposits are listed with associated percentages (to five percent) in 354 deposits. There are no data for 13 percent of the deposits.

28a (kuroko vms), 46%
none, 27%
Urals vms, 9%
Au veins, 6%

Deposit Types within 10 km—Deposit types that occur within 10 km of bimodal-mafic VMS deposits are listed with associated percentages (to five percent) in 354 deposits. There are no data for 13 percent of the deposits.

28a (kuroko VMS), 57%
none, 15%
Urals VMS, 9%
Au veins, 8%

Post-Mineral Deformation—In 354 bimodal-mafic deposits, post-mineral deformation occurs in 79 percent of the deposits and do not occur in 2 percent of the deposits. There are no data for 19 percent of the deposits.

Syn-Mineral Intrusion—In 354 bimodal-mafic deposits, syn-mineral intrusions occur in 32 percent of the deposits and do not occur in 26% of the deposits. There are no data for 42 percent of the deposits.

Post-Mineral Intrusion—In 354 bimodal-mafic deposits, post-mineral intrusions occur in 62 percent of the deposits and do not occur in 4 percent of the deposits. There are no data for 34 percent of the deposits.

Lithotectonic Setting—Bimodal-mafic deposits (354) are associated with bimodal-mafic rocks in oceanic arcs (78%) and bimodal-mafic rocks in epicontinental arcs (22%).

Mafic Volcanogenic Massive Sulfide Deposits

Tonnage—

Median: 0.74 million tonnes (174 deposits).
90th percentile: 0.03 million tonnes.
10th percentile: 15 million tonnes.

Grades—

Copper:
Median: 1.7% Cu (173 deposits).
90th percentile: 0.61% Cu.
10th percentile: 4.1% Cu.

Zinc:
10th percentile: 2.1% Zn (58 deposits).

Gold:
10th percentile: 1.7 g/t Au (71 deposits).

Silver:
10th percentile: 33 g/t (70 deposits).

Age—Range for 197 deposits—15 Ma (Miocene) to 3,200 Ma (Archean), mean 1,384 Ma, median 1,500 Ma. Period or epoch names of ages of the ore are listed with the percentage of the 197 deposits.

Cambrian, 24%
Cretaceous, 19%
Triassic-Jurassic, 11%
Proterozoic, 10%
Ordovician, 10%
Carboniferous, 6%
Silurian, 5%
Paleocene-Eocene, 7%
Devonian, 3%
Permian, 3%
Archean, 2%
Miocene, 1%

Area of Deposit—0.0002 to 3.77 km^2, median 0.02 km^2 (20 deposits).

Deposit A Axis—0.02 to 18 km (117 deposits).

Deposit B Axis—0.002 to 5 km (113 deposits).

Alteration A Axis—0.127 to 6 km (7 deposits).

Alteration B Axis—0.012 to 3.25 km (7 deposits).

Stringer Zone—Of 197 mafic deposits, an underlying stringer zone is present in 63 deposits and is not present in 79 deposits. No information about stringer zones was available for 55 deposits.

Syndepositional Controls—In 197 mafic deposits, the types of syndepositional controls include stratigraphic (73%), rock contact (12%), and faults or shear zones (5%). No information about controls was available for 12 percent of the deposits.

Host Rocks—Names of rocks in the horizon directly in contact with the ore deposit are listed with the percentage (to five percent) of the 197 deposits.

basalt flows, 44%
basalt tuff, 32%
shale-mudstone, 30%
sandstone-conglomerate, 17%
chert-exhalites-iron formation, 17%
diabase subvolcanic, 7%
andesite tuff, 6%

Overlying Rocks—Names of rocks from two stratigraphic horizons lying above the ore deposit are listed as follows.

Overlying Rock 2
Overlying Rock 1
Ore deposit

Percentages (to five percent) of the occurrence of rocks in 197 deposits are as follows.

Overlying Rock 2—No data (61%), chert-exhalites-iron formation (7%)

Overlying Rock 1—No data (29%), pillow basalt (17%), basalt tuff (11%), basalt flows (11%), chert-exhalites-iron formation (8%), graywacke (5%), tuff (5%)

Underlying Rocks—Names of rocks from two stratigraphic horizons lying beneath the ore deposit are listed as follows.

Ore deposit
Underlying Rock 1
Underlying Rock 2

Percentages (to five percent) of the occurrence of rocks in 197 deposits are as follows.

Underlying Rock 1—No data (28%), pillow basalt (20%), basalt tuff (12%), basalt flows (12%), chert-exhalites-iron formation (7%), sandstone (5%)

Underlying Rock 2—No data (58%), basalt flows (8%), pillow basalt (6%), diabase dikes (5%)

Rocks within 5 km—Rocks from regional geologic maps that occur within 5 km of mafic VMS deposits are listed with associated percentages (to five percent) in 200 deposits. There are no data for nine percent of the deposits.

pelites, 77%
clastics, 71%
mafic flows or breccia, 68%
mafic intrusions, 47%
ultramafic intrusions, 35%
carbonates, 34%
chert or iron formation, 26%
mafic pyroclastics or volcaniclastics, 23%
felsic intrusions, 23%
felsic flows or breccia, 23%
surficial sediments, 22%
intermediate intrusions, 20%
intermediate flows or breccia, 20%
undifferentiated sedimentary rocks, 9%
intermediate pyroclastics or volcaniclastics, 9%
felsic pyroclastics or volcaniclastics, 7%
undifferentiated pyroclastics or volcaniclastics, 5%

Minerals—Minerals reported in mafic VMS deposits are listed. Common minerals, such as quartz, feldspar, and calcite, are excluded. Percentages (to five percent) of the presence of minerals in 197 deposits are shown. There are no data for one percent of the deposits.

chalcopyrite, 94%
pyrite, 94%
sphalerite, 63%
pyrrhotite, 50%
chlorite, 42%
magnetite, 36%
galena, 27%
bornite, 22%
chalcocite, 21%

sericite, 20%
epidote, 17%
marcasite, 17%
covellite, 16%
hematite, 14%
limonite, 14%
malachite, 12%
cubanite, 12%
tetrahedrite, 11%
arsenopyrite, 11%
barite, 11%
copper, 10%
gold, 10%
biotite, 9%
carbonate, 9%
azurite, 8%
siderite, 8%
muscovite, 8%
tennantite, 7%
hornblende, 7%
valleriite, 6%
molybdenite, 6%
garnet, 6%
digenite, 6%
cuprite, 6%
actinolite, 6%
pentlandite, 6%
goethite, 6%
ilmenite, 5%
mackinawite, 5%
gypsum, 5%

Metamorphic Grade—Presence of metamorphic grades is listed with associated percentages (to 5 percent) in 197 mafic deposits. No information about metamorphic grade was available for 29 percent of the deposits.

greenschist, 36%
pumpellyite-actinolite, 12%
amphibolite, 7%
lower greenschist, 6%

Deposit Types within 5 km—Deposit types that occur within 5 km of mafic VMS deposits are listed with associated percentages (to five percent) in 197 deposits. There are no data for 10 percent of the deposits.

none, 51%
24a (Cyprus vms), 20%
28a (kuroko vms), 11%
24b (Besshi vms), 7%
Cyprus Mn, 7%

Deposit Types within 10 km—Deposit types that occur within 10 km of mafic VMS deposits are listed with associated percentages (to five percent) in 197 deposits. There are no data for 10 percent of the deposits.

none, 42%
24a (Cyprus vms), 21%
28a (kuroko vms), 15%
Cyprus Mn, 9%
24b (Besshi vms), 8%

Post-Mineral Deformation—In 197 mafic deposits, post-mineral deformation occurs in 79 percent of the deposits and do not occur in 1 percent of the deposits. There are no data for 20 percent of the deposits.

Syn-Mineral Intrusion—In 197 mafic deposits, syn-mineral intrusions occur in 20 percent of the deposits and do not occur in 35% of the deposits. There are no data for 45 percent of the deposits.

Post-Mineral Intrusion—In 197 mafic deposits, post-mineral intrusions occur in 40 percent of the deposits and do not occur in 15 percent of the deposits. There are no data for 45 percent of the deposits.

Lithotectonic Setting—Mafic deposits (197) are associated with pelite-mafic rocks in mature oceanic arcs (55%), mafic rocks in primitive oceanic backarcs (24%), and mafic rocks in midoceanic ridges (21%).

B. Deposit Model Country Codes and Country Names

Deposit model country code	Country name
AGTN	Argentina
ARMA	Armenia
AUNS	Australia, New South Wales
AUQL	Australia, Queensland
AUTS	Australia, Tasmania
AUVT	Australia, Victoria

AUWA	Australia, Western Australia
BLVA	Bolivia
BRZL	Brazil
CILE	Chile
CINA	China
CLBA	Colombia
CNBC	Canada, British Columbia
CNMN	Canada, Manitoba
CNNB	Canada, New Brunswick
CNNF	Canada, Newfoundland
CNNS	Canada, Nova Scotia
CNNT	Canada, Northwest Territory
CNON	Canada, Ontario
CNQU	Canada, Quebec
CNSK	Canada, Saskatchewan
CNYT	Canada, Yukon Territory
CUBA	Cuba
CYPS	Cyprus
DMRP	Dominican Republic
ECDR	Ecuador
EGPT	Egypt
ERIT	Eritrea
FIJI	Fiji
FNLD	Finland
FRNC	France
GERA	Georgia
GRBR	Great Britain
GUAT	Guatamala
GUYN	Guyana
INDS	Indonesia
IRAN	Iran
IRLD	Ireland
JAPN	Japan
KAZN	Kazakhstan
MNGL	Mongolia
MRCO	Morocco
MXCO	Mexico
MYAN	Union of Myanmar
NRWY	Norway
OMAN	Oman
PERU	Peru
PKSN	Pakistan
PLPN	Philippines
PORT	Portugal
RUSA	Russia
SAAR	Saudi Arabia
SPAN	Spain
SWDN	Sweden
TRKY	Turkey
USAK	United States, Alaska
USAL	United States, Alabama
USAZ	United States, Arizona
USCA	United States, California
USGA	United States, Georgia

USID	United States, Idaho
USME	United States, Maine
USMI	United States, Michigan
USMA	United States, Massachusetts
USNH	United States, New Hampshire
USNM	United States, New Mexico
USNV	United States, Nevada
USOR	United States, Oregon
USVA	United States, Virginia
USVT	United States, Vermont
USWI	United States, Wisconsin
UZBN	Uzbekistan
VNZL	Venezuela