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Application of grade and tonnage deposit models: the search for ore deposits possibly amenable to small-scale mining

by

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PREFACE

This report contains background material used by Michael S. Allen, Center for Inter-American Mineral Resource Investigations (CIMRI), Tucson, Arizona as an invited speaker at the Exposición Latinoamericana de Minería (EXPOMIN '90) held May 15-18, 1990 in Santiago, Chile. Applications of the methods described in this report use examples from Chile but the general techniques involved are not restricted geographically.

INTRODUCTION

Results from research in quantitative mineral resource assessment by the U.S. Geological Survey has possible application to small-scale mining. Some of these results may be applied by anyone in mining and exploration. Small-scale mining is one economic way to exploit a wide variety of ore deposit types and under a spectrum of conditions. When mineralization is of acceptable grade and the costs of production are sufficiently low to satisfy the required return on investment, even small deposits can be mined profitably.

DEFINITION OF SMALL-SCALE MINING

The definition of small-scale mining varies from country to country. Government interest in small-scale mining has been motivated by its accessibility to the general population and the perceived positive social and economic impacts (Meyer, 1980). Small-scale mining is dependent on "conditions of occurrence, institutional factors, and degree of industrialization" (Meyer, 1980). A variety of criteria have been used to classify small-scale mining. This includes:

1) operations that do not use formal accounting procedures (Chile);
2) a gross income of less than 20 million pesos for each operation (Mexico) (Meyer, 1980);
3) mines with annual production of 50,000 metric tons (mt) or less of ore (United Nations, 1972), and
4) sites with less than 10,000 hectares and daily production limits different for metal and non-metal mines and defined volumetrically different for various construction materials (Peru) (Meyer, 1980).

Complex definitions have also been developed based on the number of operators per mine--from one or two persons to as many as 100 persons (Todradze, 1980). In India, the small-scale mining output is "small" (definition in quantitative terms not given) but also commodity dependent as well. Small-scale operations typically lack 1) deep blasting, 2) heavy earth-moving equipment, and 3) do not employ more than 400 persons in an open-pit mine or 150 in an underground mine (Meyer, 1980). The contradictive nature of these definitions is apparent.

Two issues need to be considered in our discussion of small-scale mining--mineral deposit size and scale of mining. While small-scale mining may exploit large deposits, there are a group of deposit types that are amenable only to small-scale operations. By recognizing early in the exploration phase which deposits are best suited to the size and financial expectations of the investor, the explorationists are better equipped to focus on the appropriate deposit types. Many of the smaller deposits are of little interest to major mining companies, thus presenting a unique opportunity to more aggressive smaller mining groups who can often respond more rapidly to an opportunity of this type. Several deposit types have specific characteristics that are distinct enough from other deposit types in tectono-stratigraphic setting, shape of ore body, mineralogy, chemistry and (or) physical properties, such that exploration for these deposit types can be refined even further. These conditions may only be met in a selected part of the deposit and may effectively limit the percentage of the deposit that small-scale operations can work economically. For example, 20 percent of gold placers have gone through an initial phase of small-scale mining are, in turn, followed by large-scale mining (Bliss and others, 1986). Gold grades during the small-scale phase of mining of these deposits are significantly higher than the grades during large-scale mining phase of the same deposits. In fact, all mineral deposit types exhibit various types of changes in grades during mine life some which are due to economics of scale.

The focus of this study is not on small-scale mining of larger deposits but on the identification of mineral deposit types which are "naturally" small and thus appropriate for development by small-scale mining. For the purposes of this study, a deposit type is defined as appropriate for small-scale mining if over half of the member deposits tonnages fall within some preset maximum tonnage range. Therefore, the concept of deposit types and how one characterizes deposit sizes are the primary goals of this study and are reviewed below.

DEPOSIT MODELS

Within the studies of quantitative mineral resource assessment technology, mineral deposit sizes and grades should be handled in a consistent fashion to met the requirements of quantitative predictions of undiscovered resources (Harris and Agterberg, 1981; Singer and Mosier, 1981). The concept of deposit models has been important in this work, particularly in the methodology developed by Singer (1975; 1984). Models, in the broadest sense, is a "plan or form after a pattern" (Webster's Seventh New Collegiate Dictionary, 1961) or more likely by those involved in mining as a facsimiles in three dimensions (Thrush and others, 1968). The type of models used in the discussion which follows are 1) word representations which integrate a number of direct observations and 2) mathematical descriptions of things which can not be directly observed. Models of mineral deposits should be generally applicable, representative, and non-site-specific (Barton, 1986). A mineral deposit is defined as a mineral occurrence of sufficient size, grade, and with ore characteristics to have economic potential.

Descriptive model

The *descriptive model* is used to define a "deposit type" in which the member deposits share "a relative wide variety and large number of attributes" (Cox and Singer, 1986). Cox and Singer's (1986) compilation contains 85 descriptive models.

Genetic model

A *genetic model* consists of a body of concepts outlining the process and conditions involved in the formation of a mineral deposit. A genetic model may be applicable to sets of deposits described by one or more descriptive models and can impose important constraints on definition of permissible geologic settings, etc.

Grade and tonnage model

Using descriptive models, mineral deposits are classified and the data are used to develop *grade and tonnage models* that are related to the economic characteristics of the deposit. Cox and Singer's (1986) compilation contains 60 grade and tonnage models. This model type will be examined in greater detail in the follow sections.

Exploration model

The combination of the descriptive, genetic, and grade-tonnage models plus the financial and logistical constraints of a company leads to the development of the *exploration model*. These models, either formally or informally stated, give a set of conditions used to search for mineral deposits. The exploration model is formulated by the company to serve its best interests and is useful in defining which activities and tools should be used to locate the deposit type desired. Grade and tonnage models can used to predict the range of sizes and grades expected in an undiscovered deposit of a specific type and are an important part of the development of the exploration model.

APPLICATION OF A GRADE AND TONNAGE MODEL

To date, the U.S. Geological Survey has developed grade and tonnage models for 71 different mineral deposit types for which 60 can be found in Cox and Singer (1986). Data on over 3,900 mineral deposits were used in the models of Cox and Singer (1986). Grade and tonnage models are usually based on data from production and reserves and or on size and grade of deposits prior to mining (Cox and Singer, 1986). Models are graphically depicted as cumulative frequency distributions.

Figure 1-6 show an example of a newly developed grade and tonnage model that is a refinement of the grade and tonnage model of kuroko massive sulfides initially prepared by Singer and Mosier (1986a). The refined model (called Sierran kuroko) by Singer (in press) uses data from deposits in the western United States, western Canada, and the state of Alaska. For comparison, the relative position of the Toqui district, Aysen, Chile, is shown using the data in Wellmer and others (1983). The classification of Toqui in this deposit type is preliminary and it is only included to provide a Chilean example. Figure 1 is the cumulative curve for deposit tonnage. For undiscovered deposits of this type, 90 percent are expected to have at least 62,000 tonnes or more of ore, and 10 percent are expected to have 1,600,000 tonnes or more of ore. As located on figure 1, the Toqui deposit is among the larger ones. If this model is appropriate for Toqui and if undiscovered deposits of this type are present in Chile, the majority are likely to be of a smaller size and may be amendable for small-scale mining. Of the 23 deposits used for the model, 70 percent have reported zinc grades (fig. 2) and 40 percent have reported lead grades (fig. 3). Fifty percent of the deposits are expected to have a zinc grade of 2.9 percent or greater and 10 percent of the deposits are expected to have a zinc grade of 13 percent or greater. The values for lead are reported on figure 3. The zinc and lead grades for Toqui as computed from data found in Wellmer and others (1983) are shown for comparison. In 80 percent of the deposits used in the model, silver was also reported. The silver grade of the Toqui deposit falls mid-range (fig. 4). While gold grades are reported in 70 percent of the deposits (fig. 5), none is reported by Wellmer and others (1983). Reporting on Toqui is either incomplete or Toqui is simply among the 30 percent of the deposits without reported gold as shown by the model (fig. 5). All Sierran kuroko deposits have reported copper grades which are larger than the one reported for Toqui (fig. 6). As in the case of gold grades, either reporting for Toqui is incomplete or this grade and tonnage model is not appropriate.

TONNAGES BY MINERAL DEPOSIT TYPES

The deposit types are ranked from smallest to largest using median deposit tonnage size (fig. 7). Data sources include Cox and Singer (1986), Orris and others (1987), Mosier and Page (1988), and the eight models compiled by Bliss (in press). The bars display the size of 95 percent of the deposits for each model. Corresponding deposit numbers, deposit names, commodities, median tonnage, and standard deviation can be found in Table 1. For the purposes of this study, a deposit type is defined as maybe amenable to small-scale mining if over half of the member deposits are within some maximum tonnage range. To choose such deposit sizes requires other information such as grade or contained metal, price, cost, etc., for a particular small-scale mining process, therefore no attempt was made to dictate what this preset size is. However, to demonstrate the use of the methodology, deposit sizes between 3,200 and 1,000,000 tonnes were chosen for illustrative purposes (fig. 8). Note that the definition we use is restricted to deposit types where the size of the majority (but not all) of the member deposits are expected to be less than the preset maximum tonnage. While a small investor/operator with limited capital can clearly find large deposits, we are suggesting that there are a group of mineral deposits of economic interest to only small investors/operators. The shaded area on figure 8 is the 3,200 and 1,000,000 tonnes size range chosen to represent ore deposits that maybe amenable to small-scale mining.

DEPOSIT TYPES IN CHILE

Six deposit type in Cox and Singer (1986) use data from ore deposits found in Chile. These include:

(1) Porphyry Cu with data from Andacolla, Cerro Colorado, Chuquicamata, El Abra, Los Bronces, Los Pelambres, Mantos Blancos, Mocha, Pampa Norte, Quebrada Blanca, Rio Blanco, and Sierra Gorda (Singer and others, 1986),
(2) Porphyry Cu, skarn related, with data from Potrerillos (Singer, 1986),
(3) Iron skarns with data from Carmen (Mosier and Menzie, 1986),
(4) Polymetallic replacement with data from Maria Christina and Silva-Aysen (Mosier and others, 1986),
(5) Basaltic copper with data from Buena Esperanza in a descriptive model by Cox, (1986)(grade and tonnage model not available for this deposit type), and
(6) Volcanic-hosted magnetite including El Algarrobo, El Dorado, and Infiernillo (Mosier, 1986b).

Most of these deposits types (figure 9) are mined predominantly by using large-scale mining methods. A few volcanic-hosted magnetite deposits and several polymetallic-replacement deposits are smaller than 1,000,000 tonnes and thus may be amenable to small-scale mining as defined here. If Toqui is correctly classified as a Sierran kuroko massive sulfide deposit, the majority of the deposits like it are expected to be smaller than 1,000,000 tonnes.

There are other deposit types that are being mined and (or) are in the process of being described in Chile which do not have grade and tonnage models. Models for industrial minerals are particularly lacking. Some of these deposit types may be amenable to small-scale mining. While the types listed in Table 2 are by no means exhaustive, the suggestion are that there are a wide variety of mineral deposit types in Chile which may be amenable to small-scale mining.

Precious metal deposit types (with authors of associated grade and tonnage models following in parenthesis) which may be amenable to small-scale mining suspected or likely to be found in Chile are: hot-spring Au-Ag (Berger and Singer (in press)), sedimentary hosted Au (Mosier and others (in press)), epithermal quartz-alunite Au (Mosier and Menzie, 1986b), Creede epithermal veins (Mosier, Sato, and Singer, 1986), Au-PGE placers (Orris and Bliss, 1986), Comstock epithermal veins (Mosier, Singer, and Berger, 1986) and Sado epithermal veins (Mosier and Sato, 1986)(fig. 10). More Sado epithermal vein deposits are amenable to small-scale mining than other deposit types shown.

Small non-precious metal deposit types (e.g., Pb, Zn, Hg, etc.) include rhyolite-hosted Sn (Singer and Mosier, 1986b), polymetallic veins (Bliss and Cox, 1986), hot springs Hg (Rytuba, 1986), epithermal Mn (Mosier, 1986a), volcanogenic uranium (Mosier, 1986c), and sediment-hosted Cu (Mosier, Singer and Cox, 1986) (fig. 10).

SUMMARY

There are a variety of ore deposit types that have predictable grade and tonnage ranges and some deposit types may be of more interest to the large-scale mining companies, than other deposit types. Small-scale mining has an important role in the development of the mineral wealth of any region. A strategy sometimes adopted by investors with limited-risk capital is to focus on deposit types not in demand by the larger companies with larger risk capital. Should these smaller organizations find a big deposit, they always have the option to develop it with another company or sell it. Similarly, smaller deposits found by larger groups are possible acquisitions by the small-scale miner. While no statistics are readily available, the role of small-scale mining companies has been vital to the mineral resources industry. They have made important discoveries and collectively have added significantly to the total production and revenue base of various regions. Their success may be further enhanced if they consider the potential types of deposits in a region and focus on those suitable for small-scale mining and less likely to be in demand by large-scale mining companies.

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Table 1. List of deposit type number (used in some of the figures), deposit type names, commodities, median tonnage and standard deviation from grade and tonnage models. Commodities listed in parenthesis are found in less than 90 percent of the deposits used in the grade and tonnage model for the deposit type. Data are predominantly from grade and tonnage models found in Cox and Singer (1986), Mosier and Page (1988), and Bliss (in press).

NO.	Deposit Type	Commodities	Median size (tonnes)	SD
1	Minor podiform Cr	Cr2O3, (PGE)	1.30E+02	0.94
2	Simple Sb	Sb, (Au, Ag)	1.80E+02	1.11
3	Olymic Peninsula-type vol. Mn	Mn	3.40E+02	1.59
4	Francison-type volcanogenic Mn	Mn	4.50E+02	1.20
5	Rhyolite-hosted Sn	Sn	1.00E+03	0.49
6	Chugach-typ low-sulf. Au-qtz v.	Au, (Ag)	3.20E+03	0.71
7	Cuban-type volcanogenic Mn	Mn	6.40E+03	1.15
8	Polymetallic veins	Pb, Ag, (Zn, Au, Cu)	7.60E+03	1.11
9	Hot springs Hg	Hg	9.50E+03	0.92
10	Major podiform Cr	Cr2O3, (PGE)	2.00E+04	0.76
11	Replacement Mn	Mn, (Cu)	2.20E+04	1.07
12	Epithermal Mn	Mn	2.50E+04	0.79
13	Silicia-carbonate Hg	Hg	2.80E+04	1.04
14	Low-sulfide Au-quartz veins	Au, (Ag)	3.00E+04	1.15
15	Cyprus-type volcanogenic Mn	Mn, Fe	4.10E+04	1.22
16	Disseminated Sb	Sb	8.80E+04	0.82
17	PGE-Au placers	PGE, (Au)	1.10E+05	0.86
18	Besshi massive sulfides	Cu, (Ag, Au, Zn)	2.20E+05	0.98
19	Sol.-collapse breccia pipe U	U	2.30E+05	0.26
20	Sn veins	Sn	2.40E+05	1.00
21	Thorium-rare-earth veins	Th, (Nb, REE)	2.60E+05	0.96
22	Unconformity U-Au	U	2.60E+05	1.27
23	Sado epithermal veins	Ag, Au, (Cu)	3.00E+05	0.79
24	Sierran kuroko	Cu, (Zn, Ag, Au, Pb)	3.10E+05	0.55
25	Volcanogenic uranium	U	3.40E+05	0.95
26	Cu skarn	Cu, (Ag, Au)	5.60E+05	0.95
27	W vein	W	5.60E+05	0.86
28	Comstock epithermal veins	Ag, Au, (Cu)	7.70E+05	0.84
29	Homestake Au	Au, (Ag)	9.40E+05	0.82
30	Au-PGE placers	Au, (Ag)	1.10E+06	1.31
31	W skarn	W	1.10E+06	1.03
32	Creede epithermal veins	Ag, Zn, Pb, (Au, Cu)	1.40E+06	0.94
33	Zn-Pb skarn	Zn, Pb (Ag, Cu, Au)	1.40E+06	0.73
34	Kuroko massive sulfides	Cu, (Zn, Ag, Au, Pb)	1.50E+06	0.85
35	Cyprus massive sulfides	Cu, (Ag, Au, Zn)	1.60E+06	0.87
36	Epithermal quartz-alunite Au	Au, Ag, (Cu)	1.60E+06	0.66
37	Komatitic Ni-Cu	Ni, (Cu, PGE, Co, Au)	1.60E+06	0.75
38	Bedded barite	Barite	1.80E+06	0.92
39	Polymetallic replacement	Pb, Zn, (Ag, Au, Cu)	1.80E+06	0.69
40	Synorogenic-synvolcanic Ni-Cu	Ni, Cu, (Co, Au, PGE)	2.10E+06	0.71
41	Saprolite-laterite Au	Au, (Ag)	3.90E+06	0.53
42	Sn replacement	Sn	5.20E+06	0.56
43	Sandstone hosted Pb-Zn	Pb, (Zn, Ag)	5.40E+06	0.83
44	Sedimentary-hosted Au	Au, (Ag)	6.50E+06	0.66
45	Fe skarn	Fe	7.20E+06	1.05
46	Sn greisen	Sn	7.20E+06	0.75
47	Sedimentary Mn	Mn, (P)	7.30E+06	1.24
48	Distal disseminated Ag-Au	Ag (Au)	7.40E+06	0.81
49	Sn skarn	Sn	9.40E+06	0.61
50	Hot-springs Au-Ag	Au (Ag)	1.20E+07	0.63
51	Sedimentary exhalative Zn-Pb	Zn, Pb	1.50E+07	0.74
52	Sedimentary-hosted Cu	Cu, (Ag, Co)	2.20E+07	0.91
53	Karst type bauxite	Al2O3	2.30E+07	0.68
54	Laterite bauxite	Al2O3	2.50E+07	1.14
55	Serpentine-hosted Asbestos	Asbestos	2.60E+07	0.59
56	Dunite Ni-Cu	Ni, (Cu, Au, PGE, Co)	2.90E+07	0.77
57	SE Missouri Pb-Zn & App. Zn	Zn, (Pb, Ag)	3.50E+07	0.93
58	Volcanic-hosted magnetite	Fe, P	4.00E+07	0.82
59	Laterite Ni	Ni, (Co)	4.40E+07	0.59
60	Oolitic ironstone	Fe	5.50E+07	0.89
61	Carbonatite	Nb2O5, (REE)	6.00E+07	0.44
62	Porphyry Cu, skarn-related	Cu, (Ag, Au, Mo)	8.00E+07	0.47
63	Shoreline placer Ti	TiO2, (ZrO2, REE)	8.70E+07	0.70
64	Porphyry Cu-Mo, low florine	Mo	9.40E+07	0.60
65	Porphyry Cu-Au	Cu, Au, (Ag, Mo)	1.00E+08	0.47
66	Porphyry Cu	Cu, (Mo, Ag, Au)	1.40E+08	0.69
67	Superior Fe & Algoma Fe	Fe, (P)	1.70E+08	0.91
68	Climax Mo	Mo	2.00E+08	0.50
69	Phosphate, upwelling	P	3.30E+08	0.86
70	Phosphate, warm current	P	4.00E+08	0.73
71	Porphyry Cu-Mo	Mo, Au, Ag	5.00E+08	0.48

Table 2. Partial list of general deposit types (including precious metals, non-precious metals, and industrial minerals) suspected or known to occur in Chile. In some cases, a deposit-type has a corresponding descriptive model and grade and tonnage model that are listed elsewhere in this report.

Precious metal deposit types:

- Hot springs gold
- Gold placers
- Quartz-alunite gold veins
- Quartz-adularia gold veins
- Sedimentary-hosted precious metals
- Volcanic-hosted precious metals

Base and other metal deposit types:

- Hot-springs mercury
- Sedimentary-hosted copper
- Rhyolite-hosted tin
- Epithermal manganese
- Polymetallic veins
- Polymetallic replacement (manto)
- Epithermal manganese
- Sandstone uranium,

Industrial:

- Pegmatite
- Fumarolic sulfur
- Perlite
- Hydrothermal kaolin
- Alkaline lacustrine evaporates
- Neutral lacustrine evaporates
- Alkaline-lake brine
- Chilean nitrate
- Phosphate
- Saline-alkaline lake zeolite

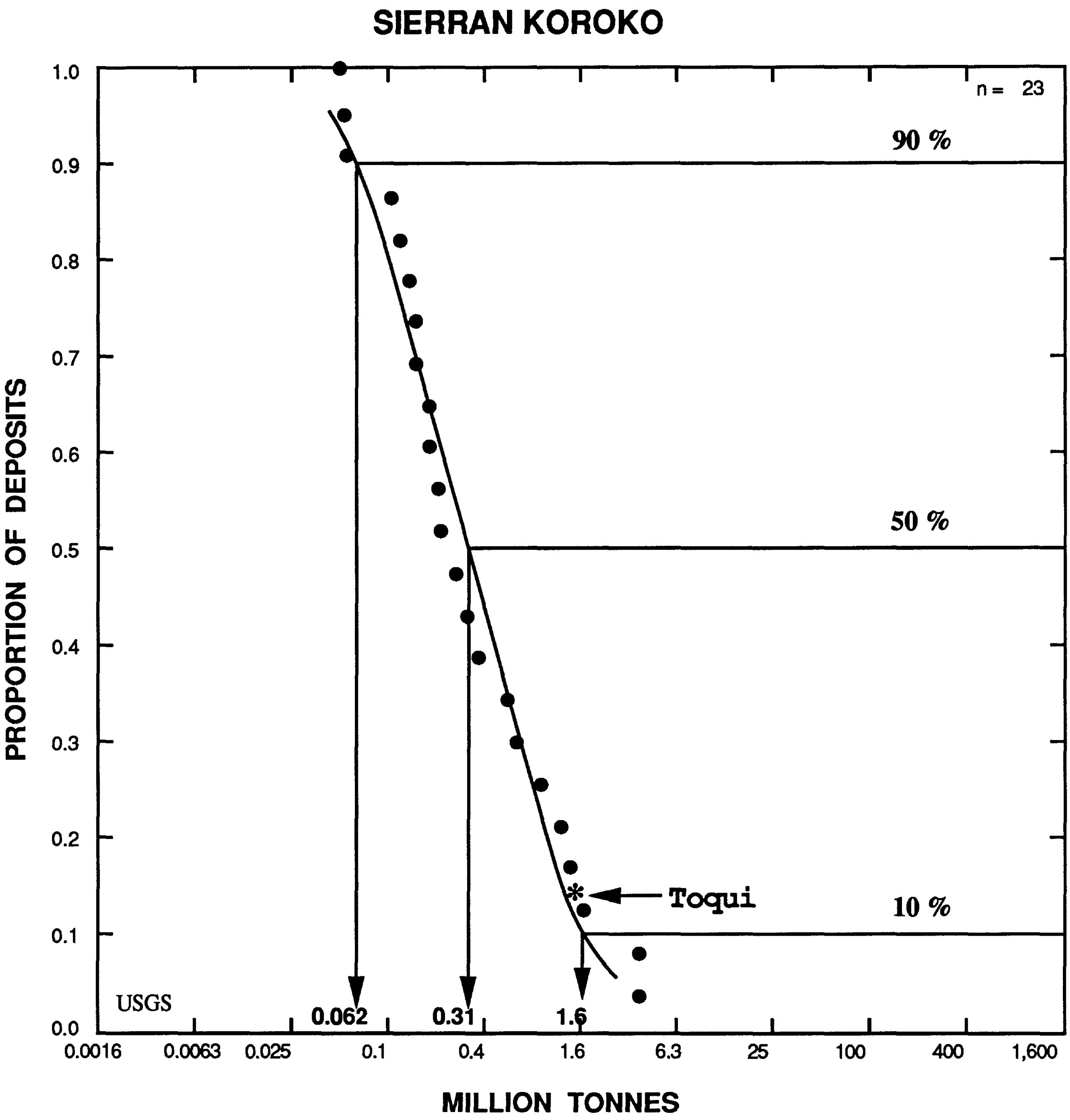

Figure 1. Tonnage of Sierran kuroko deposits (modified after Singer (in press)).

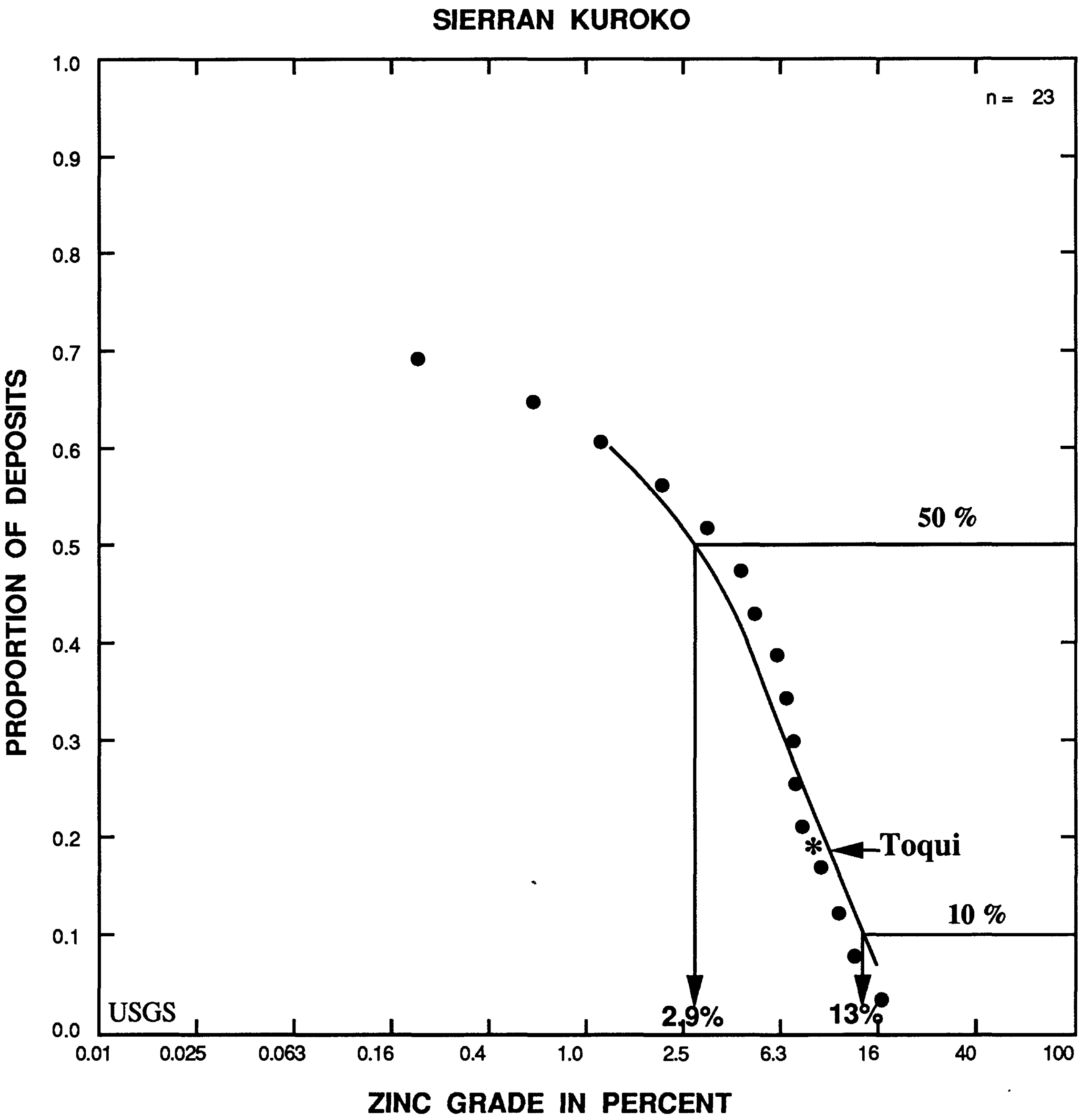

Figure 2. Zinc grades of Sierran kuroko deposits (modified after Singer (in press)).

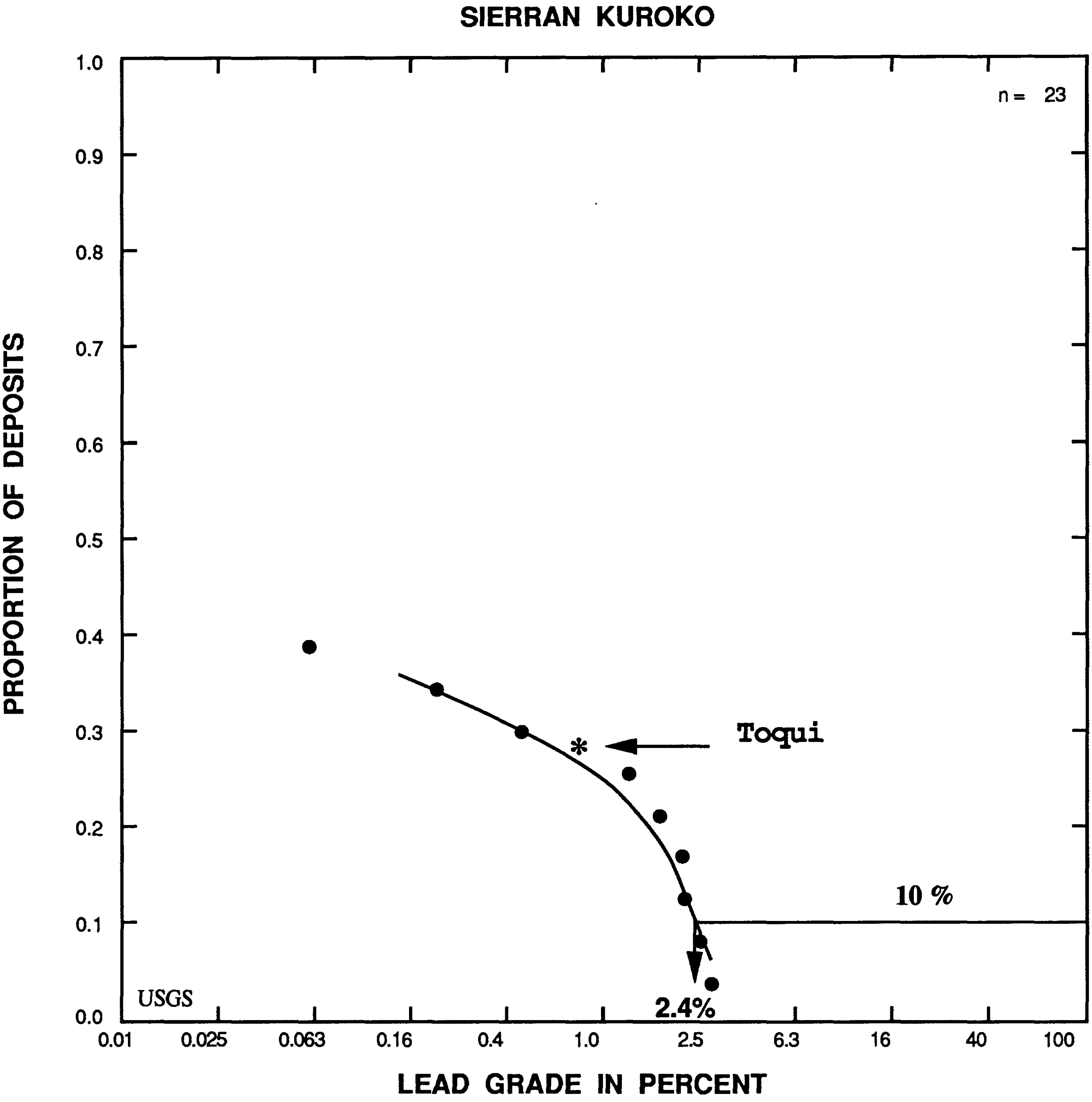

Figure 3. Lead grades of Sierran kuroko deposits (modified after Singer (in press)).

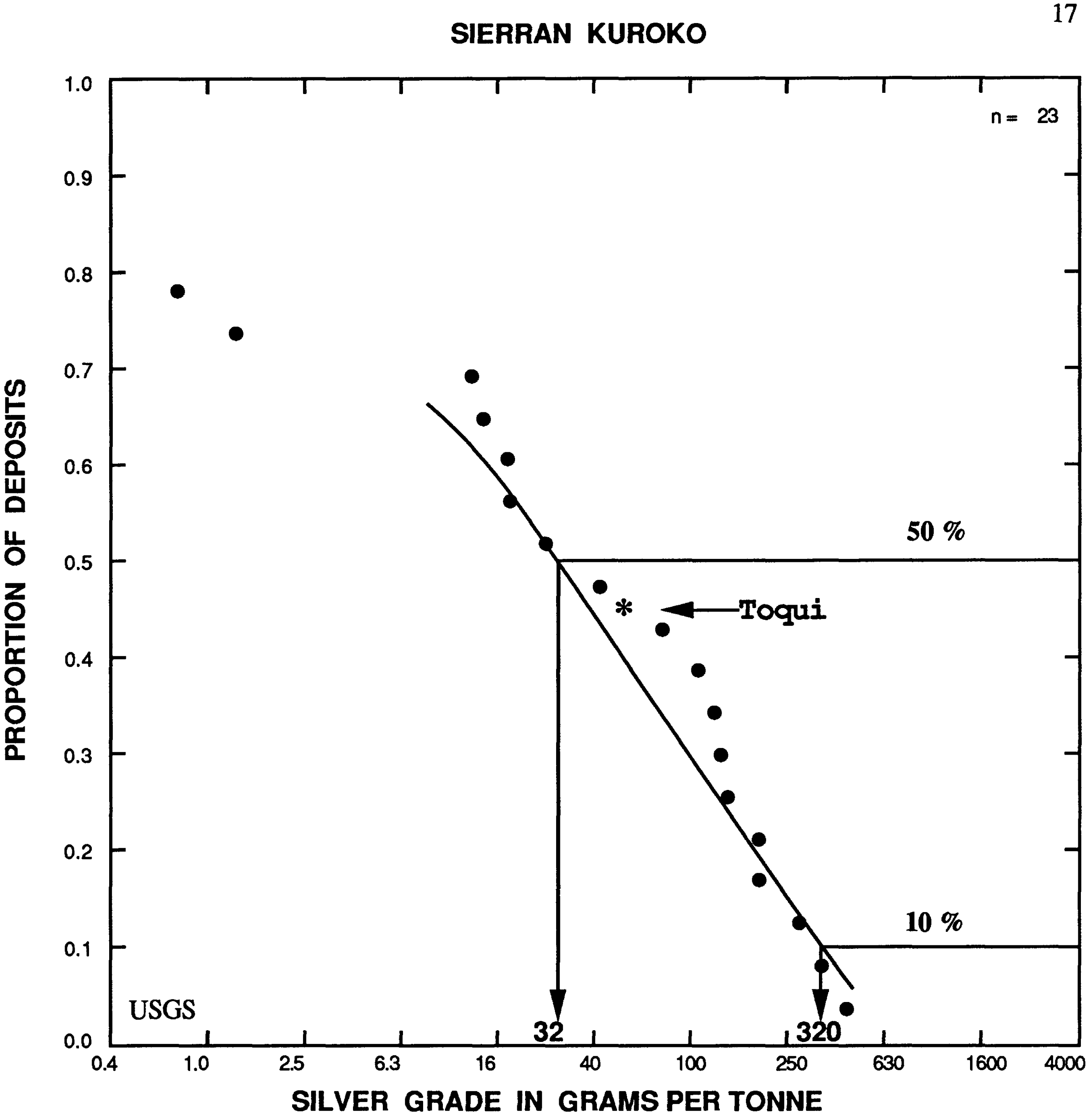

Figure 4. Silver grades of Sierran kuroko deposits (modified after Singer (in press)).

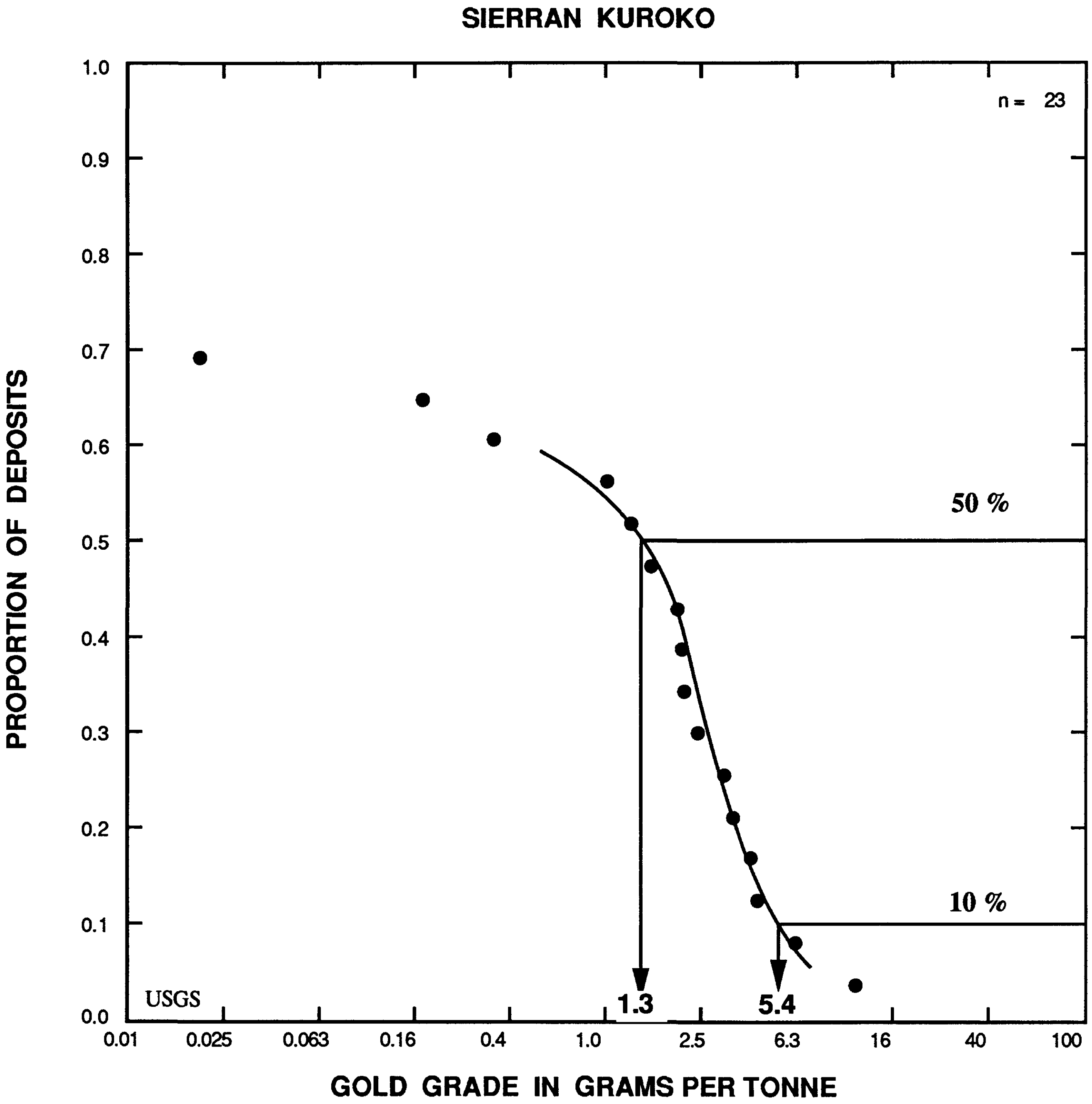

Figure 5. Gold grades of Sierran kuroko deposits (modified after Singer (in press)).

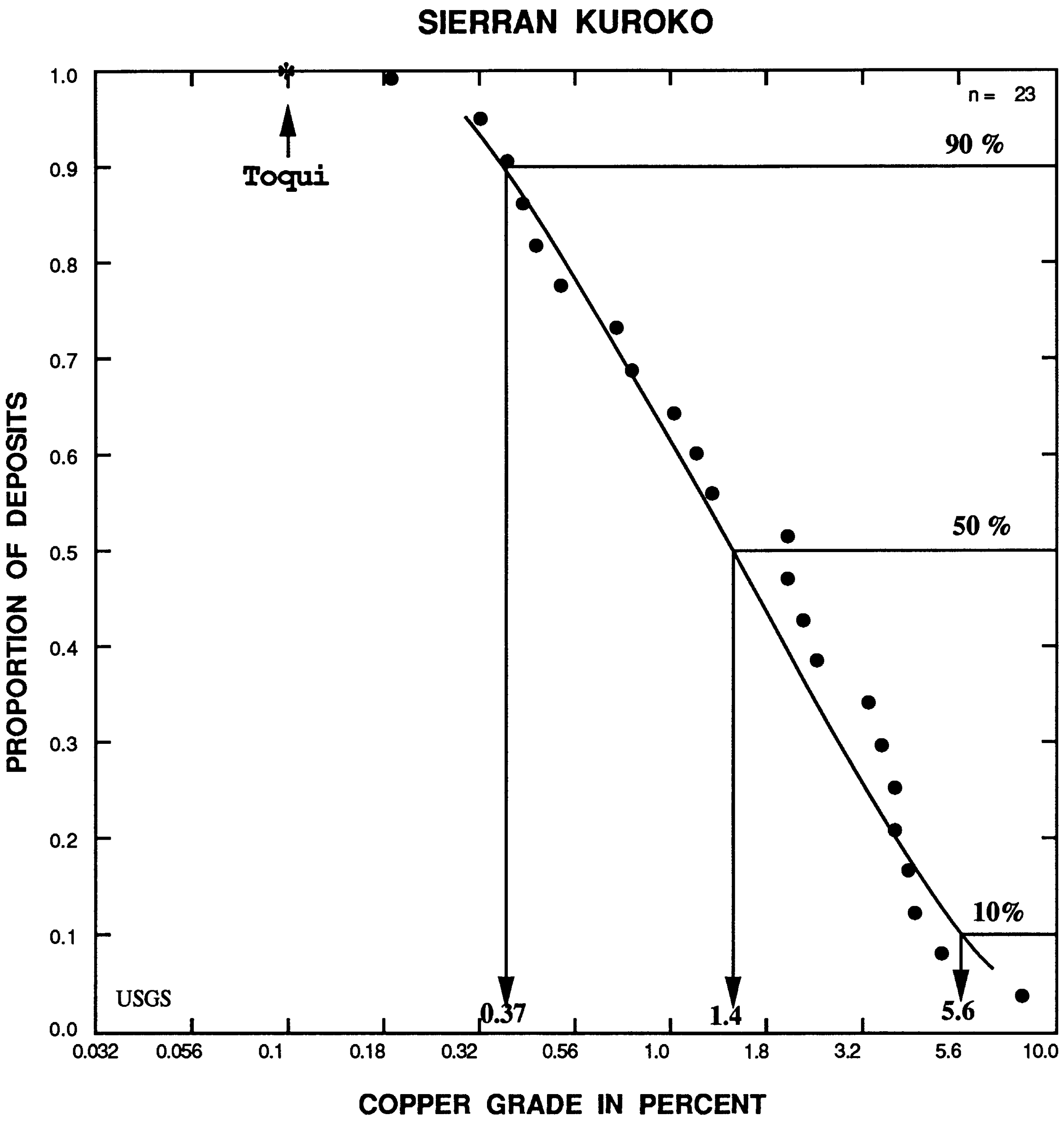

Figure 6. Copper grades of Sierran kuroko deposits (modified after Singer (in press)).

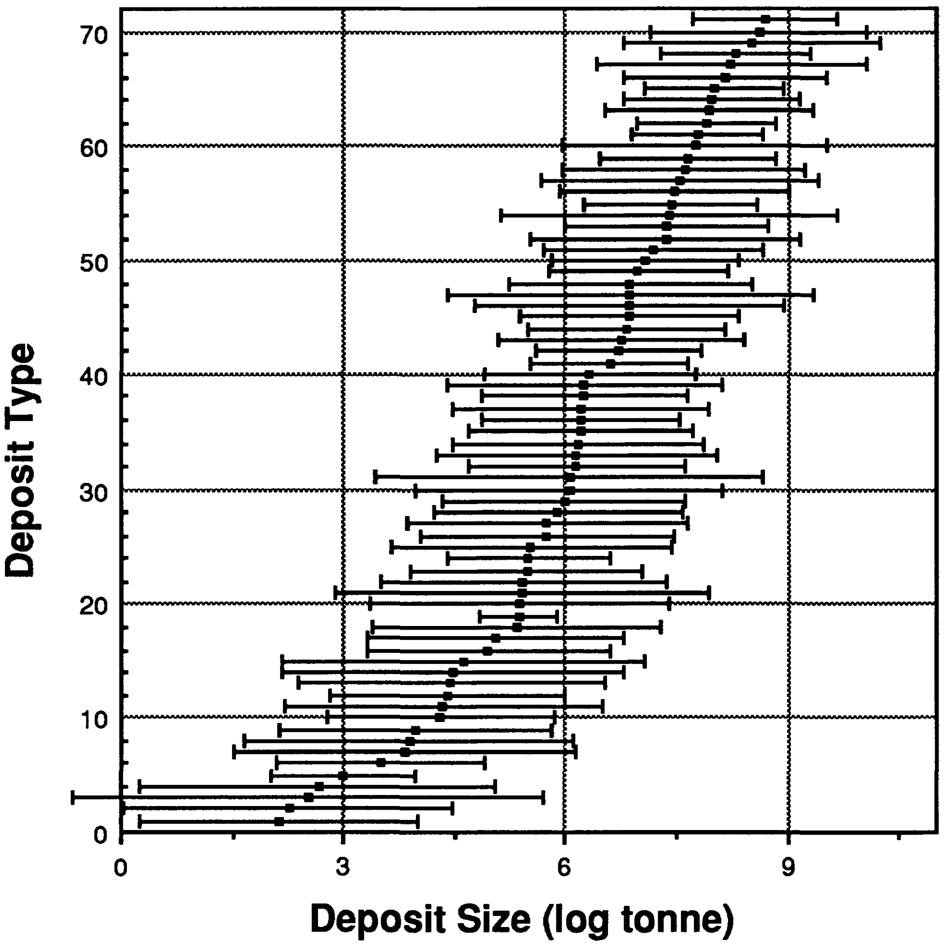

Figure 7. Tonnages of mineral deposit types ranked by the median size. Bars give the range of 95 percent of the deposits based statistics from the fitted distribution (see Table 1 for names of deposit types corresponding to numbers along the y axis).

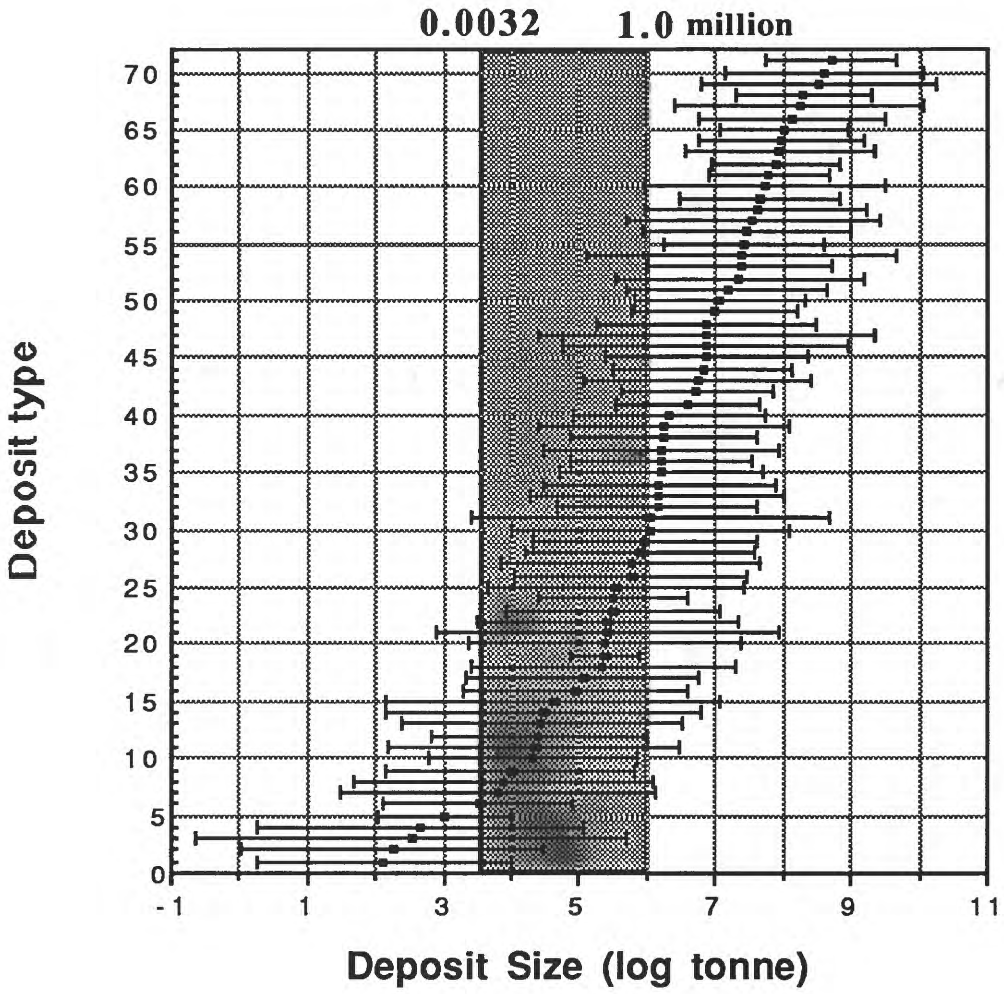

FIGURE 8. Tonnages of mineral deposit types ranked by the median size with designated range for small-scale mining range shaded from 3,200 to 1,000,000 tonnes (see previous figure for explanation of other features of the figure).

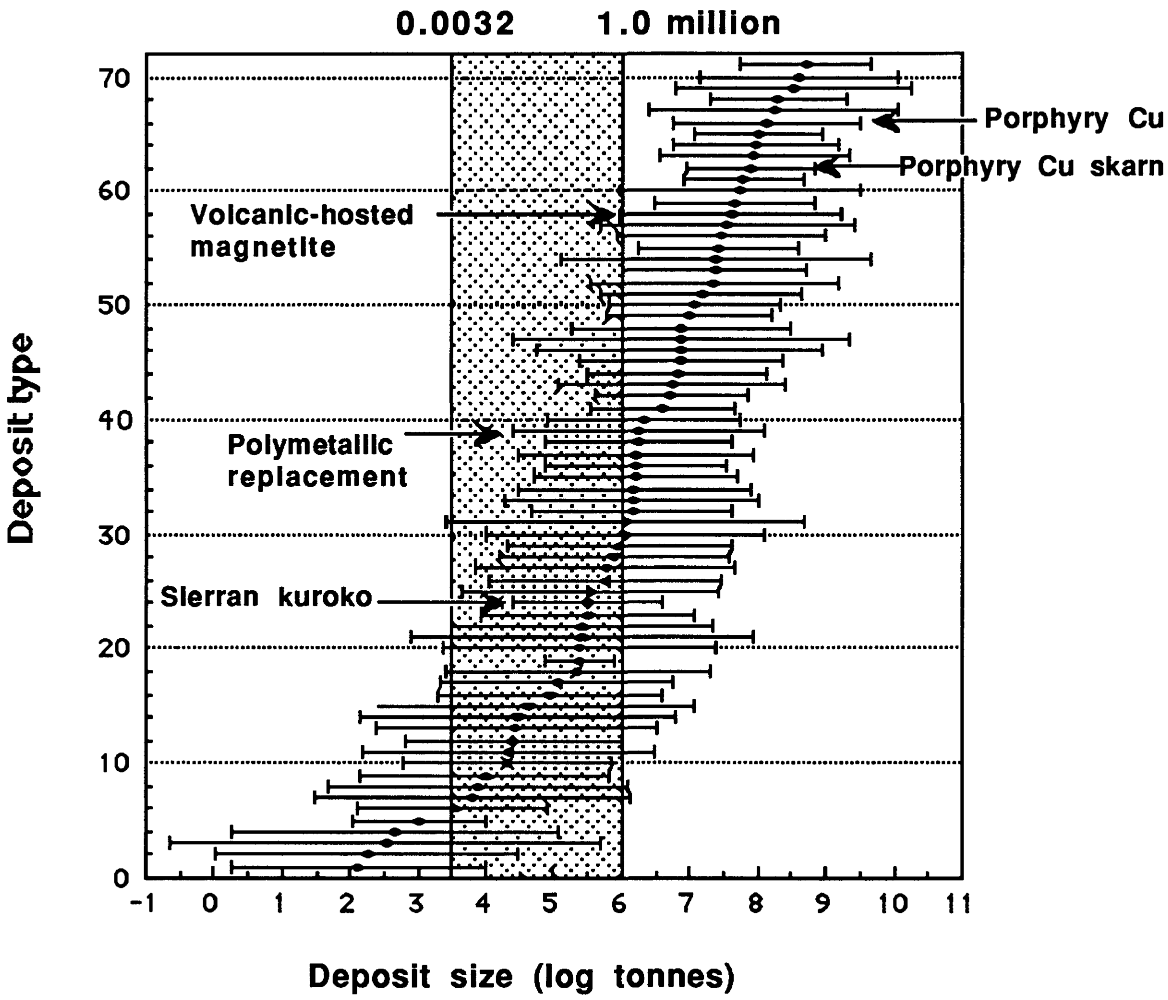

FIGURE 9. Tonnage of mineral deposit types ranked by the median size with five Chilean deposit types based on grade and tonnage models by Singer and others (1986), Singer (1986), Mosier (1986c), Mosier, Morris, and Singer (1986b), and Singer (in press). The shaded area is the selected range for small-scale mining.

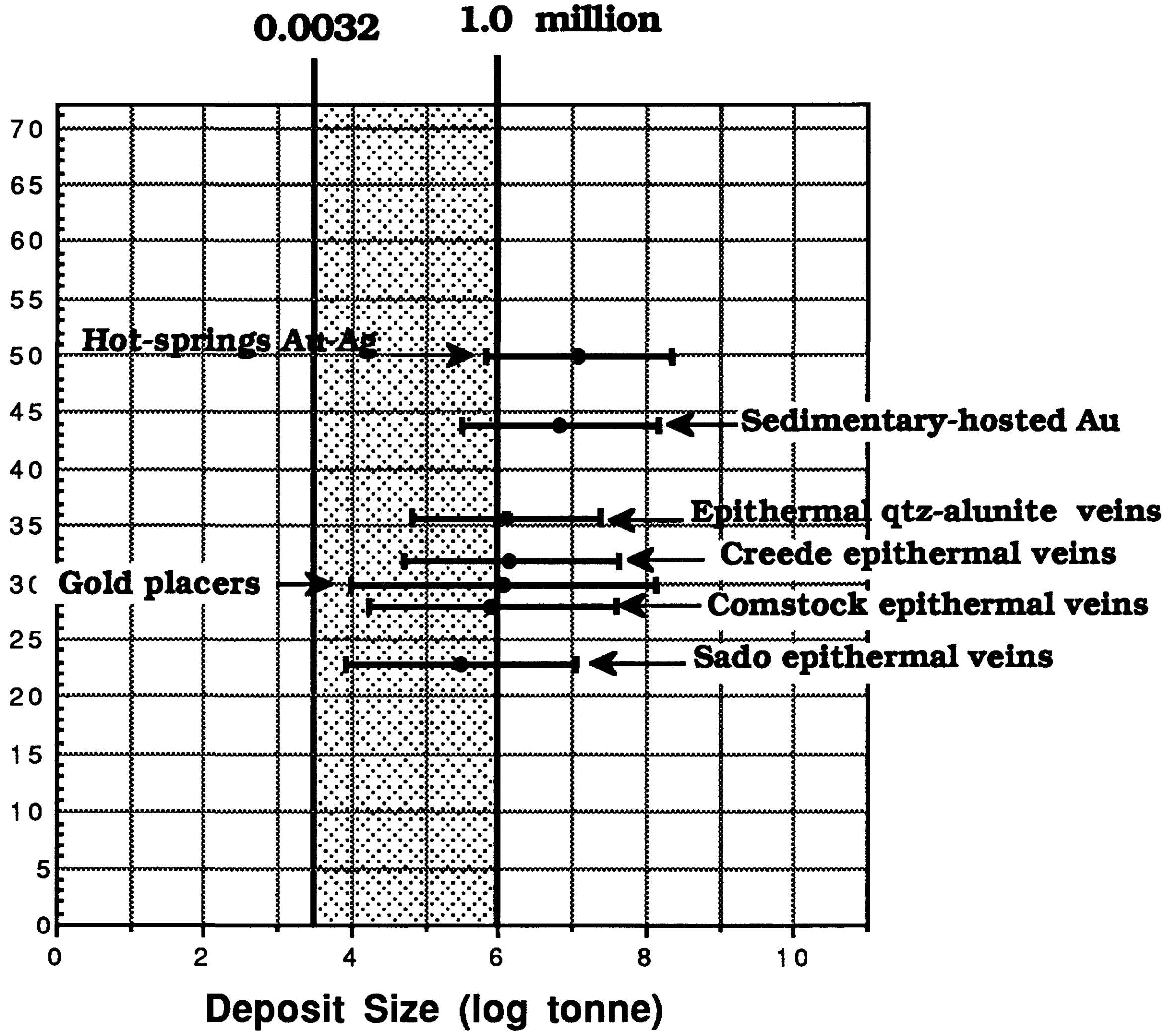

FIGURE 10. Tonnages of seven precious metal mineral deposit types ranked by the median size. Deposit types are suspected or known to be found in Chile. Size are as reported in grade and tonnage models of hot-spring Au-Ag (Berger and Singer (in press)), sedimentary hosted Au (Mosier and others (in press)), epithermal quartz-alunite Au (Mosier and Menzie, 1986a), Creede epithermal veins (Mosier, Sato, and Singer, 1986), Au-PGE placers (Orris and Bliss, 1986), Comstock epithermal veins (Mosier, Singer, and Berger, 1986), and Sado epithermal veins (Mosier and Sato, 1986). The shaded area is the selected range for small-scale mining.

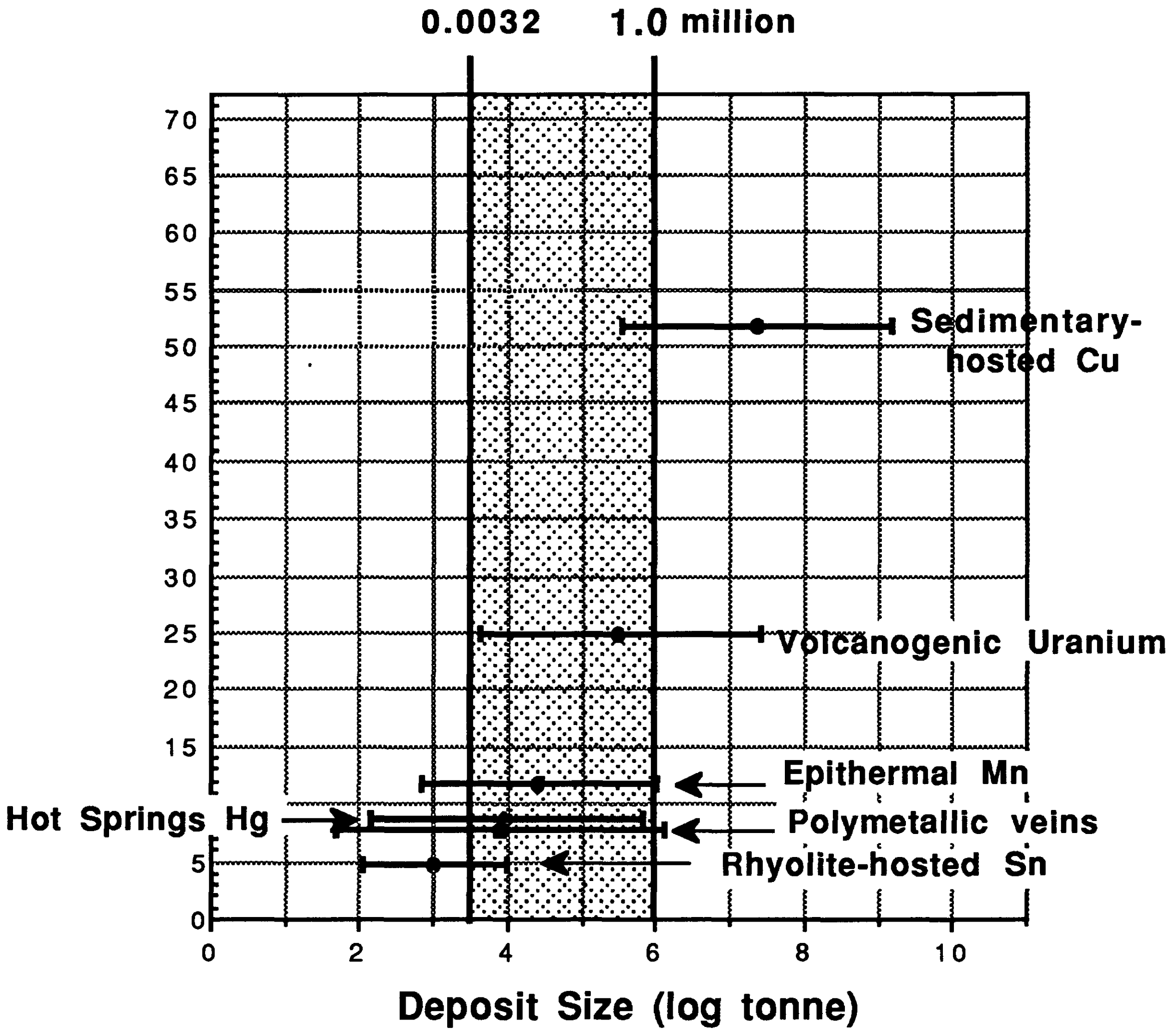

FIGURE 11. Tonnages of Six non-precious metal mineral deposit types ranked by the median size suspected or known to be found in Chile. Size based on grade and tonnage models of rhyolite-hosted Sn (Singer and Mosier, 1986), polymetallic veins (Bliss and Cox, 1986), hot springs Hg (Rytuba, 1986), epithermal Mn (Mosier, 1986a), volcanogenic uranium (Mosier, 1986c), and sediment-hosted Cu (Mosier, Singer and Cox, 1986). The shaded area is the selected range for small-scale mining.