Estimation of Undiscovered Deposits in Quantitative Mineral Resource Assessments—Examples from Venezuela and Puerto Rico

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Quantitative mineral resource assessments used by the United States Geological Survey are based on deposit models. These assessments consist of three parts: (1) selecting appropriate deposit models and delineating on maps areas permissive for each type of deposit; (2) constructing a grade-tonnage model for each deposit model; and (3) estimating the number of undiscovered deposits of each type. In this article, I focus on the estimation of undiscovered deposits using two methods: the deposit density method and the target counting method.

In the deposit density method, estimates are made by analogy with well-explored areas that are geologically similar to the study area and that contain a known density of deposits per unit area. The deposit density method is useful for regions where there is little or no data. This method was used to estimate undiscovered low-sulfide gold-quartz vein deposits in Venezuela.

Estimates can also be made by counting targets such as mineral occurrences, geophysical or geochemical anomalies, or exploration "plays" and by assigning to each target a probability that it represents an undiscovered deposit that is a member of the grade-tonnage distribution. This method is useful in areas where detailed geological, geophysical, geochemical, and mineral occurrence data exist. Using this method, porphyry copper-gold deposits were estimated in Puerto Rico.

Key words:
Resource assessment
Undiscovered deposits
Venezuela
Puerto Rico
Gold veins
Porphyry copper

Introduction

The U.S. Geological Survey bases its mineral resource assessments on mineral deposit models. Deposit models are summaries of data, in a convenient form, that describe a group of mineral deposits with similar geological characteristics. Deposit models are based on worldwide literature and observation; they contain information on the common geological attributes of the deposits and on the geological environments in which the deposits are found.

A mineral resource assessment has three parts (Singer, 1993).

Part 1: Based on a review of the geology of the study area, appropriate deposit models are selected, and permissive areas for each type of deposit are delineated. The permissive area is defined by the environments of formation described in the deposit model.

Part 2: For each model, the worldwide data on grade and tonnage are reviewed. By analogy, the undiscovered deposits in the area should be similar in grade and tonnage to the worldwide population. For many deposit types, these data are available in the form of grade-tonnage models in U.S. Geological Survey Bulletins 1693 and 2004.

Part 3: Estimates are made of the number of undiscovered deposits of each type in the permissive areas. This, the most difficult part of the assessment, is the topic of this article.

Any given area has a single, but unknown, number of undiscovered deposits. The estimates of undiscovered deposits are presented as percentiles that are opposite or complementary to percentiles as they are most commonly used. Thus the 100th percentile is assigned to an estimate of zero undiscovered deposits or more. The 10th percentile, for example, is assigned to a number of undiscovered deposits for which there is approximately a 10-percent chance of at least that number of deposits occurring. The deposits estimated should be consistent with the grade-tonnage model selected in part 2. That is, if 10 deposits are estimated, 5, on average, should be larger than the median tonnage for that deposit type, and 5 should be richer than the median grade.

Experience with three-part mineral resource assessment programs indicates that the participating geoscientists commonly have the greatest difficulty with making estimates of undiscovered deposits. A common complaint is that the estimates are untestable except by costly mineral exploration programs extending over time periods that are long in comparison to our lifetimes. Thus the estimator of undiscovered deposits rarely benefits from increased experience, as does the predictor of weather or sports scores. The purpose of this article is to present

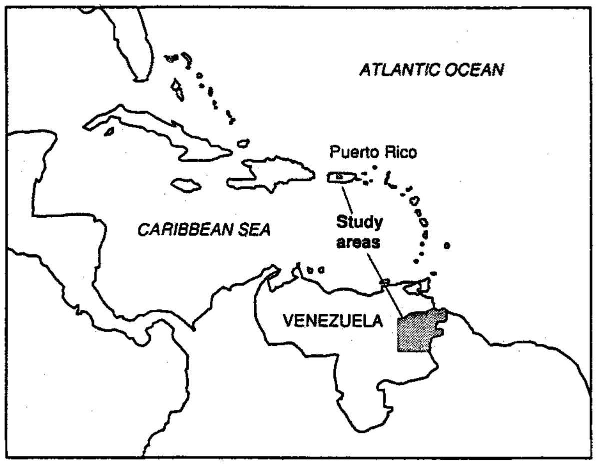

Figure 1. Map showing location of study areas in Puerto Rico and Venezuela.

some guidelines that increase confidence in these estimates and to describe two examples in Venezuela and Puerto Rico (fig. 1) in which these guidelines were used.

There are many approaches to the problem of estimating undiscovered deposits. We review two methods in this article: the density of deposit method and the target counting method. In the former, estimates are made by analogy with well-explored areas that contain a known density of deposits per unit area and that are geologically similar to the study area. The number of deposits from the known area can be used as a guide to the number of deposits that could exist in the study area. When compared to the number of known deposits and occurrences in the study area, a number of undiscovered deposits can be predicted. Some deposit densities may be close to the maximum densities, such as for massive sulfide deposits in the well-explored parts of the Hokuroku district in Japan. These can provide an upper limit to the estimates of undiscovered deposits in the study area. The deposit density method should be applied to regions where there is little data. As an example, an assessment of low-sulfide gold-quartz veins in Venezuela will be described.

Estimates can also be made by counting targets, such as mineral occurrences, geophysical and geochemical anomalies, or exploration "plays," and by assigning to each target a probability that it represents an undiscovered deposit that is a member of the grade-tonnage distribution. The sum of these probabilities is the expected number, or mean, of the estimate of undiscovered deposits. This method is useful in areas where detailed geological, geophysical, geochemical, and mineral occurrence data exist. One example, which I will discuss, is the estimate of undiscovered porphyry copper-gold deposits from a mineral assessment of Puerto Rico.

The three-part assessment results in three or more

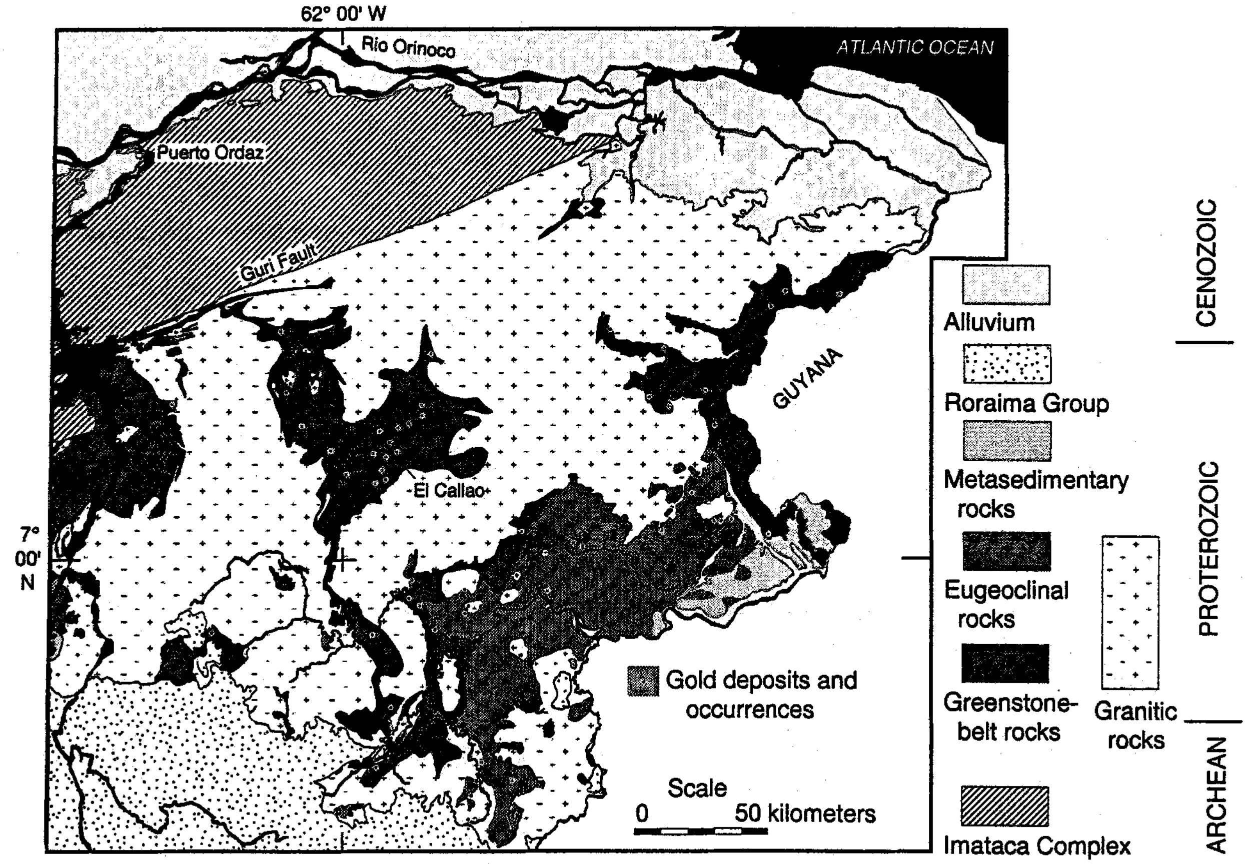

Figure 2. Geological map of the northeastern part of the Precambrian Shield of Venezuela showing the distribution of low-sulfide gold-quartz vein deposits and selected occurrences. Permissive areas are those underlain by greenstone belt and eugeoclinal rocks, shown in darker gray. Geology from Cox and others (in press).

probability distributions: number of deposits, tonnage, and grades. Sampling these distributions by computer simulation can lead to probabilistic estimates of tons of metal in undiscovered deposits in the study area (Root and others, 1992).

Venezuela: The Deposit Density Method

A 5-year mineral resource study by the U.S. Geological Survey and Técnica Minera C.A. of the Venezuelan Guayana Shield resulted in a new geological map and compilation of geophysical data at a scale of 1:1,000,000, a 500-record mineral deposit file, and a mineral resource assessment (see Wynn and others, 1991). The shield contains an Archean granulite metamorphic terrane (Imataca Complex) and a Lower Proterozoic granite-greenstone terrane (fig. 2). An overlying, locally metamorphosed, sedimentary and volcanic package composed of continental clastic rocks and voluminous, unmetamorphosed ash-flow tuffs is intruded by anorogenic granite plutons. These volcanic and plutonic rocks do not occur in the area of figure 2, but the volcanics are probably correlative with the units lumped as metasedimentary rocks. The youngest sedimentary package comprises relatively undeformed, Lower to Middle Proterozoic, continental clastic sedimentary rocks (Roraima Group) locally intruded by granites and alkaline complexes. The resource assessment was based chiefly on the following deposit models: Algoma-type iron formation in the granulite terrane; low-sulfide gold-quartz veins (LGV's) and kuroko massive sulfides in the greenstone belts; carbonatites, kimberlite pipes, and tin greisen in the overlying volcanic and sedimentary rocks; and laterite bauxite, sedimentary kaolin, and various types of placer deposits in surficial environments.

LGV deposits are veins and vein systems in shear zones in greenschist-facies metamorphic rocks of greenstone belts and eugeoclinal sequences. Gold occurs with minor pyrite and other sulfides in quartz-carbonate gangue. The grade-tonnage model for LGV deposits, compiled by Bliss (1986), is shown in figure 3. This model is based on data from 313 deposits worldwide, mainly of Phanerozoic age. LGV deposits are among the most widely distributed types of deposits known; they occur in metamorphosed eugeoclinal terranes and greenstone belts in many parts of the world. In Victoria, Australia, the Meguma terrane of Nova Scotia, Canada, and the Klamath Mountains and eastern Sierra Nevada foothills in California, U.S.A., LGV's have a density of occurrence of 4.3 to 5.4 deposits per 1,000 km² (Bliss and others, 1987) (see Table 1).

The permissive, 13,000-km² area for LGV deposits in Venezuela (fig. 2) contains Lower Proterozoic greenstones, felsic metatuffs, and mafic and ultramafic intrusions (Cox and others, in press). Grade and tonnage data for 27 LGV deposits in this area are consistent with the grade-tonnage model (Bliss, 1986) (fig. 3). To distinguish between individual deposits and extensions of known deposits, Bliss (1986) used an arbitrary rule that individual deposits be separated by one mile (1.6 km). Based on the similarity of host rocks (albeit of different age), we assume that the deposit density in the permissive area is similar to that of Australia, Nova Scotia, and California. If this is correct, the permissive area should contain from 56 to 70 deposits (table 1). Because approximately 27 deposits are known, we conclude that 29 to 43 undiscovered deposits probably exist. These estimates are reasonable, considering that 50 known occurrences in the permissive tract are classified as possible undiscovered deposits because they lack grade or tonnage information. All or some of these occurrences could be classified as deposits if future drilling indicates that they have grades and tonnages consistent with the model.

Using these numbers as guides, the study team made a subjective estimate of undiscovered deposits. We estimated that the area contains 20 or more undiscovered LGV deposits at the 90th percentile, 40 or more deposits at the 50th percentile, and 50 or more deposits at the 10th percentile that are consistent with the grade-tonnage model. The mean or expected number of deposits corresponding to this distribution is 36 (using methods of Root and others, 1992). Adding this number to the 27 known deposits gives a total of 63, a number that compares reasonably well to normalized values for the four reference areas.

This application of the deposit density method represents only a preliminary approach to the requirements for a statistically robust assessment technique. The sample size of only four control areas is inadequate to show the true variability of deposit density. The validity of the assumption of geological similarity between the control areas, which are Phanerozoic in age, and the Early Proterozoic study area is in doubt. Archean lode gold deposits, which are similar in many ways to LGV deposits, have significantly higher tonnages than their Phanerozoic counterparts (Mosier, 1986). Perhaps age-dependent geological processes affect tonnage and deposit density. The need for better data and clearer understanding of geological processes justifies an extensive research program on these topics.

Table 1. Relation between density of occurrence of low-sulfide gold-quartz vein deposits in four areas normalized to 13,000 km² and the estimate of undiscovered deposits in Venezuela.

	Number of deposits
Klamath Mountains, California (4.3/1,000 km²)	56
Sierra Nevada foothills, California (4.6/1,000 km²)	60
Victoria, Australia (5.0/1,000 km²)	65
Meguma terrane, Nova Scotia (5.4/1,000 km²)	70
Permissive area, Venezuela	
27 known deposits plus 50 occurrences	77
27 known deposits plus 36 undiscovered deposits	63

Number of deposits in the four reference areas are normalized to 13,000 km², the size of the permissive area in Venezuela.

Puerto Rico: The Counting Method

A mineral resource assessment at a scale of 1:200,000 of the island of Puerto Rico focused on the undiscovered resources in porphyry copper, epithermal gold, lateritic nickel, and other deposits (Bawiec and others, 1991). A broad area was delineated as permissive for porphyry copper deposits and within this, a smaller favorable area for porphyry copper-gold (PCG) deposits was drawn. Because of the large amount of detailed information available for this favorable area and because of the high degree of confidence in the deposit model (Cox and Singer, 1992), a separate estimate of undiscovered PCG deposits was made. This estimate is based on analysis, at a scale of 1:50,000, of geological maps, aeromagnetic maps provided by Kennecott Exploration Inc., and geochemical maps.

Porphyry copper-gold deposits in the favorable area have the following characteristic features (Cox, 1985):

1. Tertiary tonalite porphyry stocks with a quartz-rich aplitic groundmass intrude Cretaceous metabasalt or Eocene volcanic and sedimentary rocks (fig. 4).
2. Hydrothermal alteration is prominent, potassic in the central part, grading outward to propylitic. Some deposits have a cap and (or) an outer zone of phyllic or argillic alteration.
3. Chalcopyrite, as well as magnetite or pyrite, occur with quartz in stockwork veinlets. Molybdenite-bearing stockworks are rare.
4. Peripheral small polymetallic veins that contain chalcopyrite, sphalerite, and galena plus silver and gold occur up to several kilometers from the porphyry deposit.

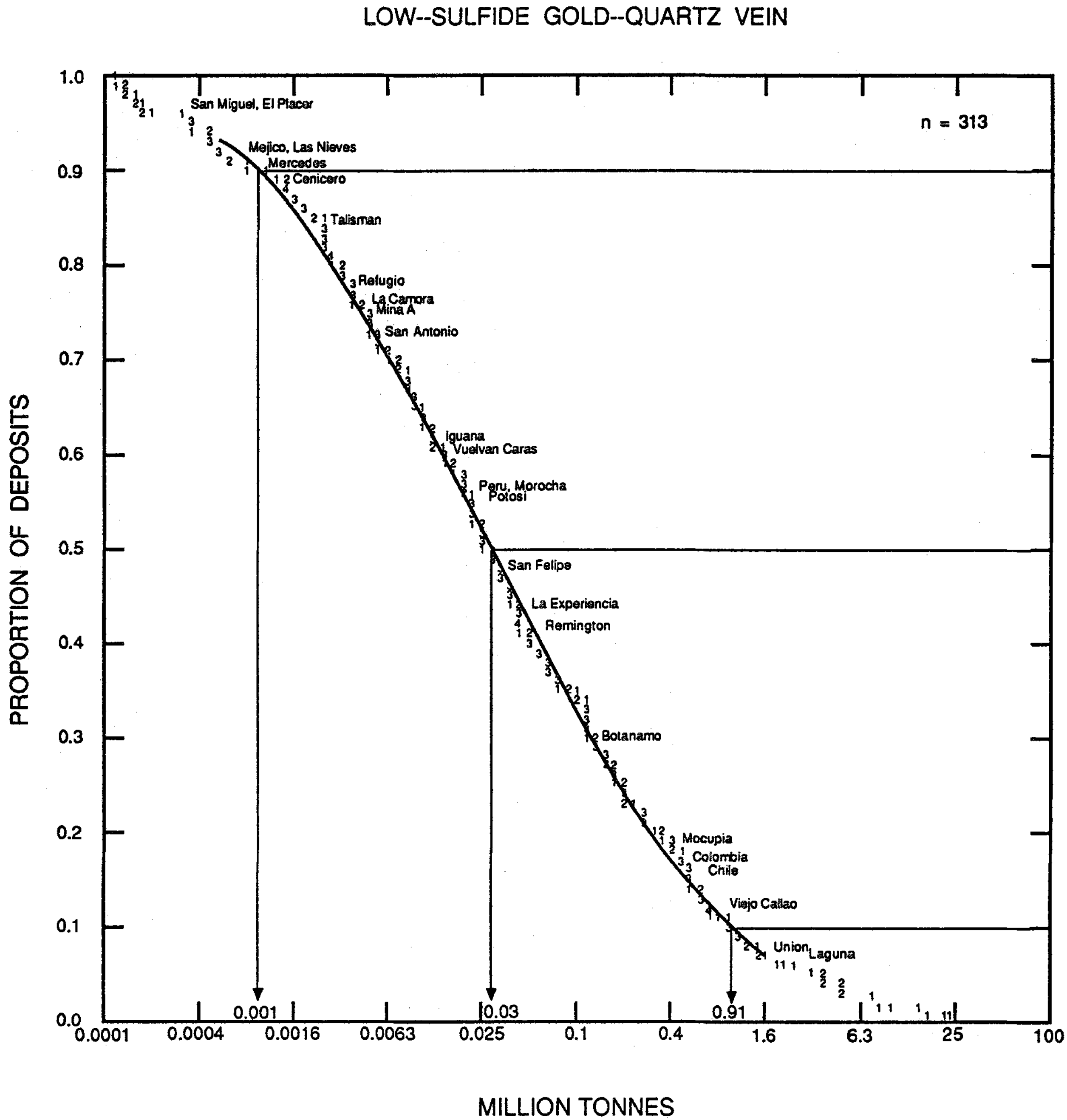

Figure 3. Grade-tonnage model for low-sulfide gold-quartz vein (LGV) deposits after Bliss (1986). Small numbers represent individual deposits from worldwide data. LGV deposits in Venezuela are positioned along the curves according to the tonnage and grade of their past production and reserves.

5. An aeromagnetic high is associated with the stock and is accentuated by magnetite mineralization in the ore bodies.
6. In some areas (Helecho), the central magnetic high is surrounded by a low that results from the replacement of magnetic iron minerals by pyrite in the peripheral phyllic and argillic alteration zones.
7. Chemical analysis of sediments from streams draining deposits shows anomalous copper and gold associated with more weakly anomalous molybdenum. Some deposits do not produce stream sediment anomalies probably because of dilution in active streams. The strongest anomalies were found near a relatively small deposit (Laundry Creek). Weak, peripheral anomalies of zinc, silver, and manganese are present, probably derived from polymetallic veins.

The two most completely explored deposits, Tanamá and Río Viví, were drilled in the 1960's. Their tonnages, copper grades, and gold grades (table 3) are consistent

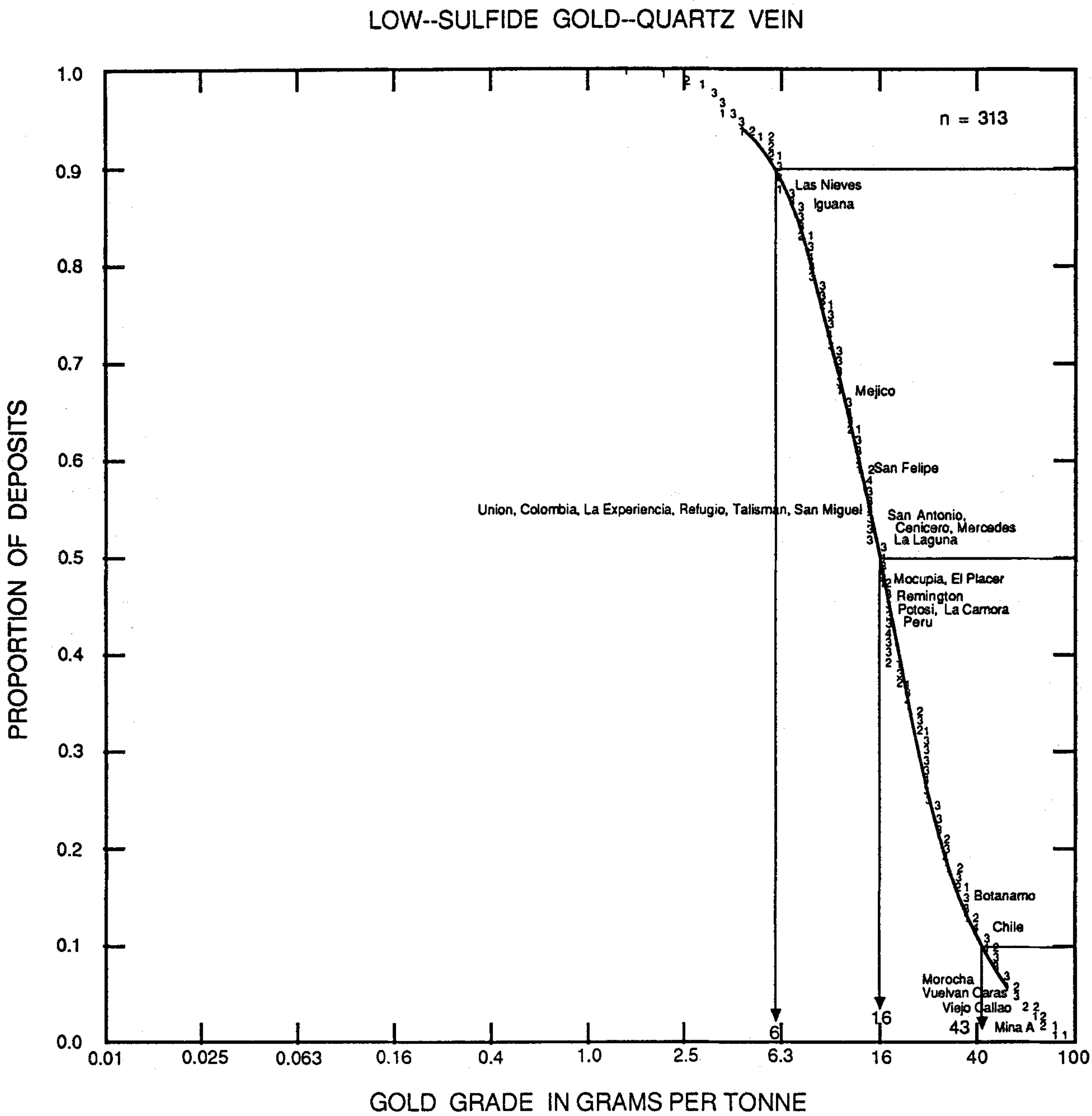

Figure 3. Continued.

with the grade tonnage model for PCG deposits of Singer and Cox (1986).

Twenty-four targets within the favorable area that may contain undiscovered PCG deposits are shown on figure 4 and briefly described in table 2. To each target, we assigned a probability that it contains an undiscovered deposit with a tonnage and grade consistent with the grade-tonnage model of Singer and Cox (1986). This assignment was made subjectively, based on the degree to which the target exhibited the seven features previously listed or otherwise matched areas of known deposits in the permissive tract.

Tanamá and Río Viví (targets 11 and 22, fig. 4), which contain deposits with published tonnages and grades consistent with the model, were assigned zero probabilities because it is not possible for an additional undiscovered deposit to exist there. Helecho (target 12) was assigned a high probability because, although a tonnage and grade has not been published, maps based on Kennecott drill-hole data (Cox, 1985) show that the deposit almost certainly belongs to the model. Laundry Creek (target 4) contains a small body of ore-grade material, about 70 by 250 m in size. Laundry Creek was given a low probability because its tonnage is likely to be too low to fit the grade-tonnage model.

A high probability was assigned to the Criminales East

Table 2. Geological, geophysical, and geochemical characteristics of favorable areas, and the probability of undiscovered deposits within the favorable tract for porphyry copper-gold deposits in the Lares-Adjuntas areas, Puerto Rico, shown in figure 4.

Map no.	Name	Geology	Aeromagnetic anomalies	Mineral occurrences	Stream sediment geochemistry	*p*[D]
1	Magos	Tv, poorly exposed	5 highs, 500–1,000 m diam. suggest igneous intrusions	None known	ND	.01
2	Piletas	Covered by Lares Lms, located on Tanamá-Laundry Creek trend	4 highs 500–1,000 m diam. similar to pattern over known deposits	None known	ND	.50
3	Lares East	Tv, poorly exposed	High	None known	ND	.01
4	Laundry Creek	Ti stock, potassic alteration in small area	Complex pattern of high and low anomalies	Cp in quartz stockwork; indicated 5–10 million tonnes at >0.4 percent Cu	Cu > 1,000; Au 0.006–0.01; plus Mo, Zn, Pb, Ag, and Mn	.1
5	Matilde	Ti stock, no alteration, poorly exposed	Broad high	None known	Cu 70–300; Zn 300–500	.05
6	Platanos	Tv, plus small intrusives in a broad area of propylitic and phyllic alteration, two prominent unaltered Ti stocks	Broad low, 1.5 × 6 km; west part correlates with alteration; highs correlate with Ti stocks	Cp in small veins	Cu 300–1,000; Zn 100–300; Mo downstream	.3
7	Copper Creek	Kv, Ti stock, potassic alteration	Small high	Quartz-mt stockwork, Cu stains; ore-grade Cu in one drill hole	Cu > 1,000; Au 0.006–0.01	.1
8	Río Piedras	Mainly Tv, poor exposures	High	None known	Cu 70–300	.01
9	Criminales East	Mainly Kv, small Ti bodies, extensive breccia (0.6 × 1.5 km), phyllic alteration	Broad low, 1.5 × 2 km, in area that interupts a trend of highs	Up to 0.34 percent Cu in outcrop	Cu 300–1,000; Zn 300–500; Au 0.006–0.01; Mn > 2500	.6
10	Copper Creek Southeast	Ti stock, local potassic alteration	South flank of arcuate high	None known	Cu 300–1,000	.1
11	Tanamá	Ti stock intruding Kv, potassic alteration on north side, phyllic and argillic to south	Strong high	Known porphyry copper-gold deposit	Cu 300–1,000 on northeast; weak Zn	.00
12	Helecho	Ti stock, potassic alteration, surrounded by Tv with phyllic and argillic alteration	Isolated high surrounded by lows	Known porphyry copper-gold deposit, reserves not published	Cu, 70–300; Mn > 2,500; weak Zn	.95
13	Cerro La Mira	Ti, poorly expressed	High	None known	Cu 70–300; Zn 100–300	.05
14	Helecho East	no exposures	High	None known	Weak	.01
15	Portillo West	Tv, poorly exposed	Small high, surrounded on west by lows	None known	ND	.01
16	Guayabo Dulce	Tv, alteration	No significant character	None known	Cu 70–300	.01
17	Palo Seco	Ti, poorly exposed	High	None known	Weak	.01
18	Upper Tanamá	Tv, poorly exposed	No significant character	None known	Cu 300–1,000; Mn > 2,500	.2
19	Cerro Lloroso	Ti stock	High	None known	Cu 70–300	.01
20	Río Arecibo	Large, complex Ti porphyry stock	High	Cp and py in veins	Cu 70–300; Au 0.006–0.01; Mn > 2,500; plus Zn, Ag	.2
21	Pellejas	Ti, Kv, and Tv	Isolated high on south side	Cp and py in veins	Cu 300–1,000; Mn > 2,500	.2
22	Río Viví	Ti stocks intruding Kv and Tv, widespread alteration	Elongate high on south side	Known porphyry copper-gold deposit	Cu 300–1,000 on south side	.00
23	El Blanco	Small Ti stock	High	Cu stains	Weak	.01
24	Jauca	Small Ti stocks	High	Fe skarn	Au 0.006–0.01; weak Cu	.05

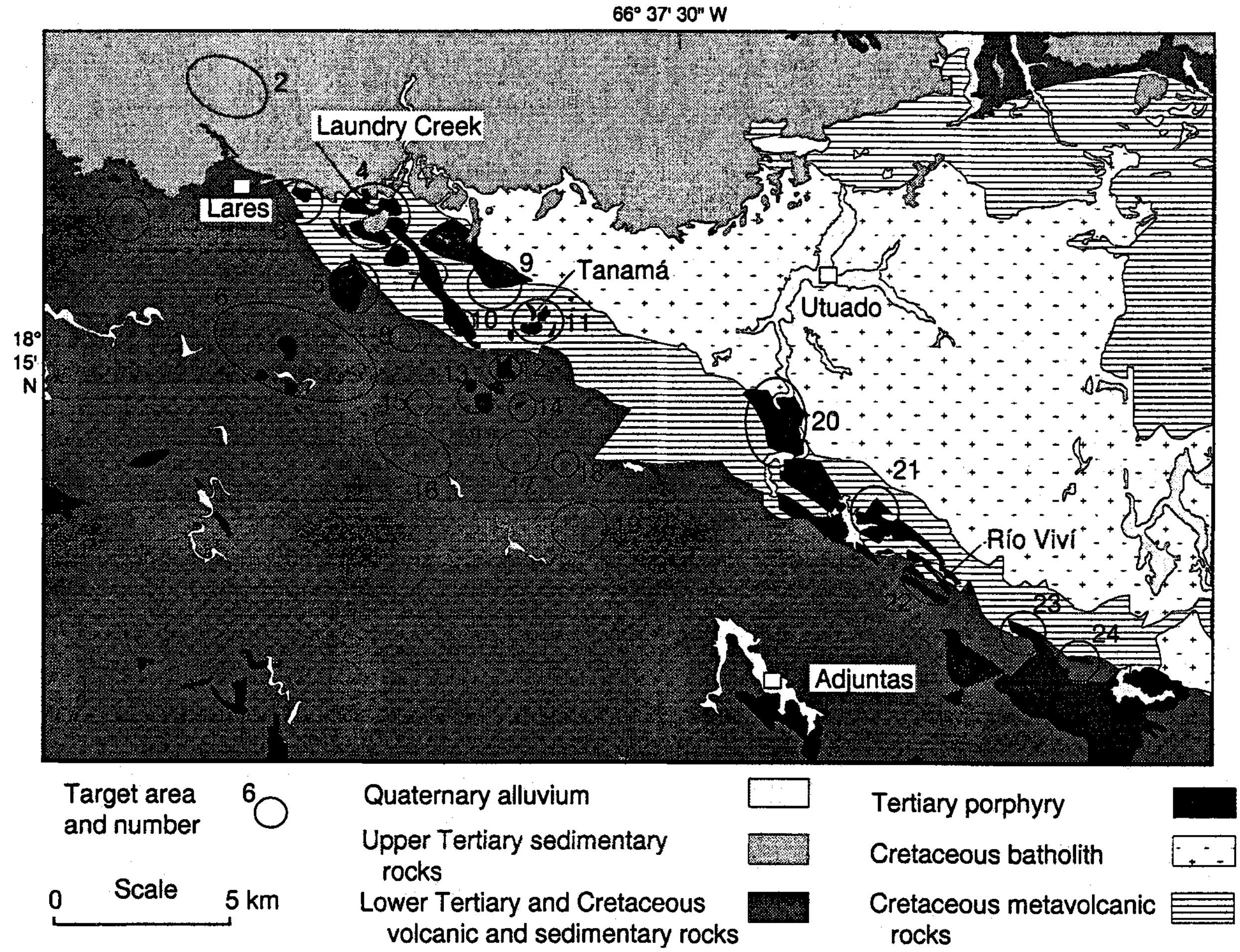

Figure 4. Geological map of the Lares-Utuado-Adjuntas area, Puerto Rico, from Cox (1985) and Mattson (1968), showing principal porphyry copper-gold deposits and target areas. Numbers refer to descriptions and estimates in table 2.

area (target 9) where a breccia body with pervasive phyllic alteration, disseminated pyrite, and anomalous copper content (Cox, 1985, p. 10) corresponds to a large aeromagnetic low shown on aeromagnetic maps provided by Kennecott Exploration Inc. These data suggest the existence of a large porphyry system at depth. A high probability was also assigned to Piletas (target 2), which is covered by about 300 m of Oligocene sedimentary rocks. This area includes aeromagnetic anomalies that are similar in form to highs associated with PCG systems to the southeast. The target is on strike with the Río Viví, Tanamá-Laundry Creek trend (fig. 4) and is situated 11 to 12 km northwest of Tanamá. This distance is similar to the distance between Tanamá and Río Viví, a fact that supports the probability of a deposit at Piletas. A periodic 15-km spacing of deposits of this type along the Quesnel structural trend has been noted in British Columbia, Canada [David G. Bailey, Geological Consultants (Canada) Ltd., oral commun., 1992].

The sum of the probabilities shown in table 2 is 3.5. This is equal to the expected number of PCG deposits in the permissive tract (Neter and Wasserman, 1954, p. 209). Estimates of 2 deposits at the 90th percentile, 3 deposits at the 50th percentile, 5 deposits at the 10th percentile, 8 deposits at the fifth percentile, and 10 deposits at the first percentile are consistent with the geological conditions, the estimated probabilities, the expected number of deposits, and the probabilities calculated by the methods of Root and others (1992). Table 3 shows estimates of the number of deposits, metal endowment

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Tv, Tertiary volcanic and sedimentary rocks; Ti, Tertiary porphyritic intrusive rocks; Kv, Cretaceous volcanic rocks; Ki, Cretaceous plutonic rocks of Utuado batholith; TKd, Tertiary and Cretaceous diorite intrusions. Stream sediment geochemical values in parts per million; Cu, copper; Zn, zinc; Au, gold; Ag, silver; Fe, iron; Mo, molybdenum; Mn, manganese; cp, chalcopyrite; py, pyrite; mt, magnetite; ND indicates no data. *p*[D] is the probability of an undiscovered deposit.

Table 3. Estimates of number of deposits, contained metal estimates by Monte Carlo simulation, and gross in-place value for known and undiscovered deposits in Puerto Rico.

	Known deposits	Undiscovered deposits 90-percent chance	50-percent chance	10-percent chance
Tonnes of ore per deposit	139 million and 100 million	25 million or more	100 million or more	400 million or more
Copper grade, percent	0.7 and 0.8	0.35 or more	0.50 or more	0.72 or more
Gold grade, ppm[a]	0.38 and 0.2	0.2 or more	0.38 or more	0.72 or more
Number of deposits	2	2 or more	3 or more	5 or more
Tonnes of copper	1.7 million	0.6 million or more	2.4 million or more	7.4 million or more
Tonnes of gold	71	32 or more	180 or more	580 or more
Gross in-place value[b]	$2.6 billion	$1.6 billion or more	$7 billion or more	$23 billion or more

[a] ppm = parts per million.

[b] Copper at $1.00 per pound; gold at $300 per ounce.

estimates derived by Monte Carlo simulation (Root and others, 1992), and gross in-place value of known and undiscovered deposits in the favorable area.

Application of the counting method in this study depended on the experience of a few economic geologists working in the area intermittently over a 30-year period; estimates of probabilities were made subjectively. To make this technique available to a wider group of investigators, some of whom may lack this level of experience, better and more quantified deposit models are needed.

Geochemical research in Puerto Rico has illustrated the complex dispersion patterns of copper, gold, and other elements in stream sediments and soils around PCG deposits. We now know that the presence of a copper anomaly in stream sediments is not a necessary attribute of a deposit, but that widespread gold anomalies in soils is probably a sufficient attribute (Learned and Boissen, 1973). More data are needed to define the probability of a deposit given a geological, geochemical, or geophysical attribute. For this we must measure the probability of occurrence of that attribute given a deposit and given a barren area. Chung and others (1992) have discussed the application of Bayesian statistics to this type of mineral deposit data for use in resource assessment.

Conclusions

The techniques we have outlined are important because they provide geological constraints on the estimation process and assure the participants that they are not "just making wild guesses." Yet, as shown, the techniques are crude and require extensive data collection and testing before they can be used with confidence.

Exploration managers and government decisionmakers should be given the best estimates possible; geoscientists with experience in the study area and knowledge about mineral deposits are the best source of these estimates. The U.S. Geological Survey is continuing an active program to provide better deposit models, including deposit density models, as well as better methods of interpreting geological, geophysical, and geochemical data, to refine our abilities in estimating undiscovered deposits.

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