PAN-AMERICAN QUANTITATIVE MINERAL RESOURCE ASSESSMENT OF COPPER, MOLYBDENUM, GOLD, AND SILVER IN UNDISCOVERED PORPHYRY COPPER DEPOSITS IN THE ANDES MOUNTAINS, SOUTH AMERICA

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Working together, the geological surveys of Argentina, Chile, Colombia, Peru, and the United States used the U. S. Geological Survey three-part mineral resource assessment methodology (Singer, 1993) to delineate the regional locations and make probabilistic estimates of the amounts of copper, molybdenum, silver, and gold in undiscovered porphyry copper deposits in the Andes. Quantitative information on the probable locations and amounts of undiscovered mineral resources of the world is important to exploration managers, land-use and environmental planners, economists, and policy makers.

ASSESSMENT METHODOLOGY

The three-part form of mineral resource assessment includes: (1) delineation of tracts where the geology is permissive for the occurrence of undiscovered porphyry copper deposits; (2) selection of grade and tonnage models appropriate for estimating amounts of metals contained in the deposits; and (3) probabilistic estimation of the number of undiscovered mineral deposits consistent with the grade and tonnage model. Thereafter, a Monte Carlo simulation computer program (EMINERS) is used to obtain probability distributions of the amounts of undiscovered metals and mineralized rock in each tract. The assessment method was developed to express probabilistically the degree of uncertainty associated with estimates of numbers of undiscovered mineral deposits and contained mineral resources, which then can be used to conduct quantitative economic evaluations of resources in a format usable by decision makers.

Porphyry copper deposits form in island and continental volcanic-arc subduction-boundary zones. Consequently, broad igneous arcs that formed at approximately the same time in such subduction settings are the fundamental unit for delineating tracts of land permissive for the occurrence of these deposits. Permissive tracts were drawn in the Andes at a scale of 1:1,000,000 that include areas of land where the geology, projected to 1 km depth, is permissive for the occurrence of undiscovered porphyry copper deposits (fig. 1) and the probability of a deposit being outside of the tract is negligible. Some tracts were subdivided where reasons exist to suspect spatial differences in the uncertainty, density, or probability of occurrence of undiscovered deposits within a tract. The assessment teams drew 26 tracts that the data suggested would be permissive for the occurrence of undiscovered porphyry copper deposits of a similar age grouping and geologic setting. Data used included the distribution of discovered deposits, prospects believed associated with porphyry systems, similar-aged intrusive and volcanic rocks of comparable magmatic arcs, similar-aged altered rocks, fault and tectonic control, available geophysics and geochemistry, and regional geologic and deposit-model experience. The amount, types, and availability of exploration information and knowledge were reviewed and evaluated, as was the distribution and thickness of younger geologic cover such as alluvium or ash-flow sheets.

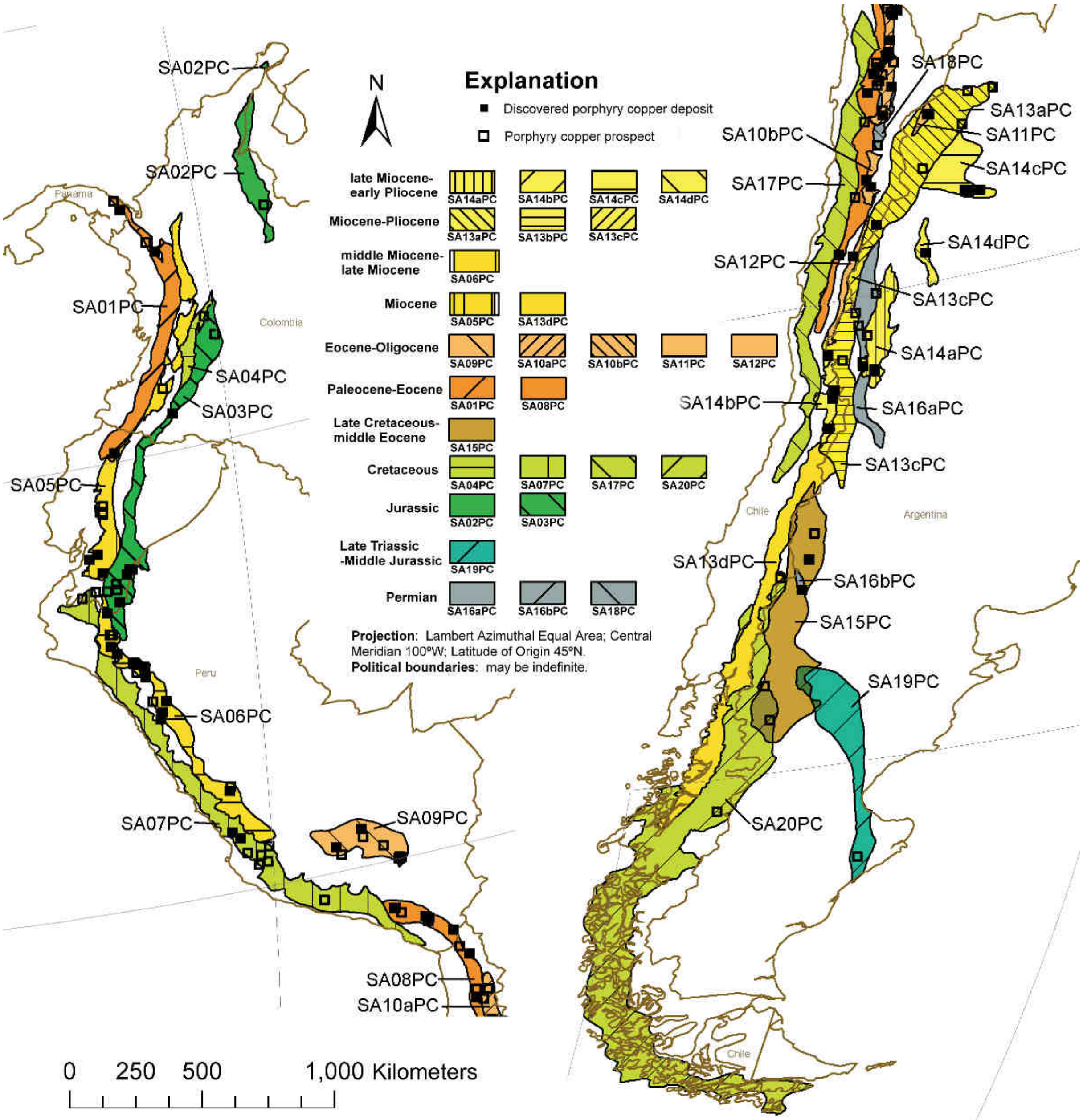

FIGURE 1. Map showing tracts permissive for the occurrence of porphyry copper deposits in the Andes Mountains by age. Tracts are numbered. Known porphyry copper deposits and prospects are shown; see text for details.

Frequency distributions of tonnages and average grades of well-explored deposits of a given type are employed as models for grades and tonnages of undiscovered deposits of the same type in geologically similar settings. For the Andes, a general model based on 380 porphyry copper deposits (Singer, Berger, and Moring, 2005) incorporating all porphyry copper subtypes was selected for most tracts because the grade and tonnage characteristics of the discovered deposits in most tracts best fit the grades and tonnages of this general model. If the size and grade of discovered porphyry copper deposits in a tract were not significantly different from the general model as determined by a t-test with $\alpha = 0.01$, the general model was used to represent the undiscovered deposits. In tracts with no discovered deposits, we assume that the general model is the best representative of the undiscovered deposits because we have no basis for selecting a more specific model. The results of t-tests of the discovered deposits in tracts 10a,b (Chuquicamata) and 14b (El Teniente) show that these deposits have tonnages and (or) grades significantly higher than the general model. Consequently, a new giant porphyry copper deposit grade and tonnage model was constructed and used to represent the grades and tonnages of undiscovered deposits these two tracts.

Table 1. Estimated numbers of undiscovered deposits in tract 1— Colombia, Ecuador, Panama (see figure 1).

Deposit type assessed: Porphyry copper	**Model:** General porphyry copper deposit model (Singer, Berger, and Moring, 2005)
Tract name: Colombia Paleocene–Eocene Acandi	**Countries:** Colombia, Ecuador, Panama
Tract ID: SA01PC	**Region:** South America
Date of assessment: May 16-18, 2005	**Date of last revision:**
Assessment depth: 1 km	
Assessment team leader: Donald A. Singer	**Regional coordinator:** Charles G. Cunningham
Estimators: Carlos Mario Celada, Vladimir I. Berger, Joseph A Briskey, Charles G. Cunningham, Donald A. Singer, David M. Sutphin, Waldo Vivallo S., and Eduardo O. Zappettini.	

Estimated numbers of undiscovered deposits by quantile. Also showing calculated mean (*m*), standard deviation (*s*), and coefficient of variation in percent (*Cv%*). Sorted by mean.

Estimators	90	50	10	*m*	*s*	*Cv%*
Estimator	2	5	10	5.47	2.97	54
Estimator	3	5	12	6.30	3.49	55
Estimator	3	8	18	9.30	5.49	59
Consensus of estimators	**3**	**8**	**19**	**9.60**	**5.87**	**61**
Estimator	5	10	20	11.17	5.59	50
Estimator	4	7	25	11.23	8.00	71
Estimator	4	12	20	11.73	5.64	48
Estimator	2	10	25	11.97	8.19	68
Estimator	4	10	25	12.43	7.72	62

Deposit density

Mean of consensus estimates of undiscovered deposits	Number of discovered deposits	Total number of deposits	Area, km²	Deposit density, number of deposits/100,000km²
9.6	2	12	51,613	23

Estimates of numbers of undiscovered deposits most commonly are based on some form of analogy whereby estimators use experience from other similar areas, together with knowledge of the numbers of deposits in those areas, to make estimates for the new areas (Singer, 2007). Information about percentage and depth of cover, the extent and kind of exploration that has taken place, and the number of prospects present are considered for each tract. Deposit densities from very well explored control areas worldwide were used as a guide where appropriate (e.g., Singer et al., 2005; Singer, 2008). Following lengthy deliberations, estimators made independent estimates consistent with the grade and tonnage models of the number of undiscovered deposits at the 90th, 50th, and 10th percentiles, which are defined as percent chance that at least the indicated number of deposits are present (table 1).

The estimates were discussed among the group and a group consensus of the best estimates at these percentiles was agreed upon. Statistical procedures were used to calculate the expected mean number of undiscovered deposits in the tract, which can be considered a measure of favorability. Two measures of uncertainty also are calculated—the standard deviation and the coefficient of variation in percent. These procedures are described in Singer and Menzie (2005).

Amounts of copper, molybdenum, gold, and silver in porphyry copper deposits yet-to-be discovered in each tract are estimated using a Monte Carlo simulation computer program (EMINERS). This program combines the probability distributions of the estimated number of undiscovered deposits with the grade and tonnage distributions associated with each deposit grade and tonnage model to obtain probability distributions for undiscovered metals in each tract (fig. 2, table 1) (Root et al., 1992; Duval, 2004).

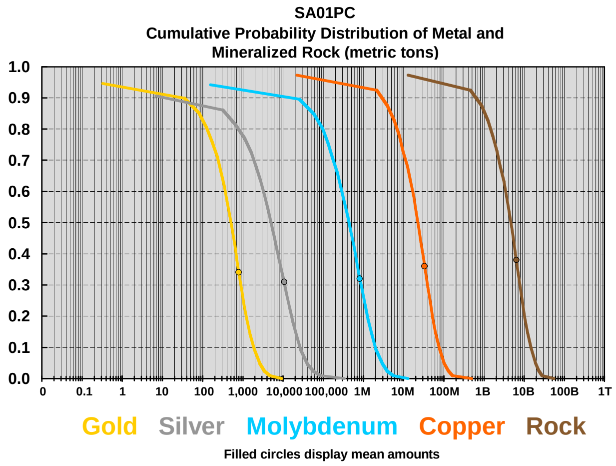

Figure 2. Cumulative probability distribution graph of estimated undiscovered metals, and mineralized rock containing the metals, in metric tons, for tract 1. Such graphs are especially useful because they show all of the information generated by the EMINERS Monte Carlo simulation.

SUMMARY OF RESULTS

There were 69 discovered porphyry copper deposits in the Andes at the time of the assessment according to the rules set forth (Singer, Berger, and Moring, 2005) to define a porphyry copper deposit in contrast to a prospect (table 3). This assessment estimates that about 145 additional deposits remain undiscovered.

There are about 590 million metric tons of copper in discovered porphyry copper deposits in the Andes (table 3). About 190 million metric tons are in 57 deposits in 16 tracts of the general porphyry copper deposit model type whereas about 400 million metric tons are in 12 deposits in 2 tracts characterized by a new giant model type. In addition, this study estimates that there are approximately 750 million metric tons of copper in undiscovered deposits of these two types in the Andes. This undiscovered copper resource is the sum of the mean estimated undiscovered copper in each of the 26 tracts. About 470 million metric tons of copper are estimated to occur in 137 undiscovered deposits in 24 tracts of the general porphyry copper type, plus another 280 million tons in 8 estimated undiscovered deposits in 2 tracts of the giant porphyry copper type. The total known and estimated undiscovered copper in the Andes amounts to an endowment, or grand total, of about 1.3 billion metric tons (table 3). Although the majority of this endowment is in the two giant tracts, this assessment estimates that nearly two-thirds of the undiscovered copper is in tracts of the general model type.

The porphyry copper resources of the Andes region are not evenly distributed in space or time (fig. 3; table 3). The Chuquicamata tract (10a,b) and the El Teniente tract (14b) stand out as containing exceptionally large deposits of discovered and estimated undiscovered copper. The greatest endowment of copper is in tract 10a,b with about 460 million metric tons, followed by tract 14b with about 220 million metric tons. The next largest copper endowments are in tract 8, which contains an endowment of about 98 million metric tons of copper, and in tract 6 with an endowment of about 96 million metric tons. The estimated undiscovered copper remaining to be found in these four tracts is: tract 10a,b, 210 million metric tons; tract 14b, 69 million; tract 6, 49 million, and tract 8, 43 million. About 90

Table 2. Tabular summary of assessment results from EMINERS Monte Carlo simulation for tract 1 (see table 1 and fig. 2). The quantiles, multiplied by 100, are equivalent to percentiles; e.g., the 0.90 quantile = 90th percentile.

Summary of Assessment Results

The tract ID is_____________ SA01PC
The EMINERS model is_____ General porphyry copper (Singer and others 2005)

Consensus Estimates:
There is a 90% or greater chance of 3 or more deposits.
There is a 50% or greater chance of 8 or more deposits.
There is a 10% or greater chance of 19 or more deposits.

Mean Number of Deposits = 9.6

Estimated amounts of contained metal and mineralized rock (metric tons)

Quantile	Cu	Mo	Au	Ag	Rock
0.95	760,000	0	0	0	190,000,000
0.90	3,100,000	23,000	34	67	680,000,000
0.50	23,000,000	440,000	510	5,000	4,700,000,000
0.10	76,000,000	2,000,000	1,854	26,000	15,000,000,000
0.05	100,000,000	2,800,000	2,600	38,000	19,000,000,000
Mean	33,000,000	810,000	790	11,000	6,400,000,000
Probability of mean or more	0.36	0.32	0.34	0.31	0.38
Probability of zero	0.03	0.06	0.05	0.09	0.03

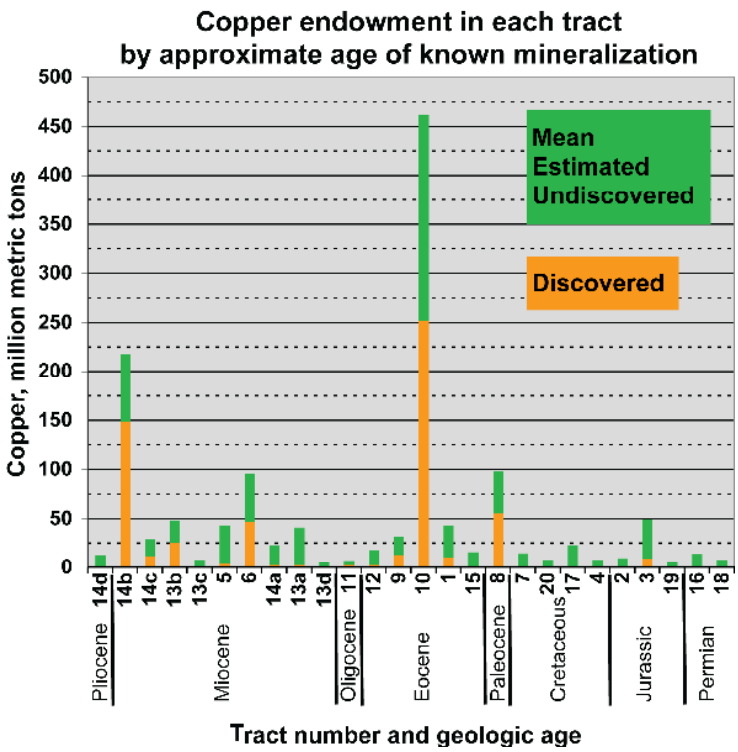

Figure 3. Column chart comparing copper endowment of each tract by approximate age of known mineralization. Tracts are arranged from youngest (left) to oldest (right) using the midpoint age of dated deposits and prospects, or using the midpoint age of the tract's host rocks where there are no dated deposits or prospects (tracts 7, 13c, 13d, 17, and 20). Horizontal axis is not linear. The a,b designations for tracts 10 and 16 to aid plotting. Data from table 3.

Table 3. Summary of principal assessment results.

Tract no.[1]	Host-rock age[2]	Ages of dated deposits and prospects, Ma	Estimated number of undiscovered deposits[3] and calculated statistics					No. of discovered deposits	Total deposits[6]	Area of tract in km²		Total discovered Cu reserves and resources in 1,000t	Mean estimated undiscovered Cu in 1,000t	Cu endowment = discovered + undiscovered in 1,000t	Mean estimated undiscovered Cu in t/km²	Mean estimated undiscovered Mo in 1,000t	Mean estimated undiscovered Mo in t/km²	Mean estimated undiscovered Au in t	Mean estimated undiscovered Au in t/km²	Mean estimated undiscovered Ag in t	Mean estimated undiscovered Ag in t/km²	Mean estimated mineralized rock, million t[7]	% undiscovered Cu[8]
			90	50	10	Mean[4]	Cv, %[5]																
01	Paleocene-Eocene	38-55	3	8	19	9.6	61	2	12	51,613	23	10,000	33,000	43,000	640	810	16	790	0.015	11,000	0.21	6,400	77%
02	Jurassic	144	1	3	5	2.9	51	0	2.9	26,631	11	0	9,700	9,700	360	240	9	230	0.0086	3,100	0.12	1,900	100%
03	Jurassic	141-166	6	11	20	11.8	45	5	17	67,709	25	9,000	40,000	49,000	590	980	14	970	0.014	13,000	0.19	7,800	82%
04	Cretaceous	131	1	2	4	2.2	54	0	2.2	10,968	20	0	7,700	7,700	700	190	17	180	0.016	2,600	0.24	1,500	100%
05	Miocene	7-20	6	11	19	11.5	42	4	16	58,797	27	4,100	39,000	43,000	660	970	16	950	0.016	13,000	0.22	7,700	90%
06	middle–late Miocene	7-20	8	13	25	14.6	45	12	27	53,186	51	47,000	49,000	96,000	920	1,200	23	1,200	0.023	16,000	0.30	9,700	51%
07	Cretaceous		1	3	8	3.9	69	2	5.9	107,297	5	600	14,000	15,000	130	340	3	320	0.0030	4,200	0.039	2,700	96%
08	Paleocene–Eocene	51-64	6	11	22	12.4	49	12	24	69,087	35	55,000	43,000	98,000	620	1,100	16	1,000	0.014	14,000	0.20	8,400	44%
09	Eocene–Oligocene	31-38	3	5	9	5.4	44	6	11	30,154	36	13,000	19,000	32,000	630	470	16	440	0.015	6,200	0.21	3,700	60%
10a,b	**Eocene–Oligocene**	**31-44**	**3**	**5**	**11**	**6.0**	**52**	**10**	**16**	**25,690**	**62**	**250,000**	**210,000**	**460,000**	**8,200**	**6,300**	**250**	**1,300**	**0.051**	**70,000**	**2.7**	**27,000**	**45%**
11	Eocene–Oligocene	29-31	0	1	3	1.3	90	1	2.3	2,429	95	3,000	4,200	7,200	1,700	100	41	100	0.041	1,400	0.58	810	58%
12	Eocene–Oligocene	34	2	4	8	4.5	52	1	5.5	6,913	80	3,000	15,000	18,000	2,200	360	52	360	0.052	4,700	0.68	2,900	83%
13a	Miocene–Pliocene	14-15	4	8	24	11.3	66	1	12	70,587	17	2,900	38,000	41,000	540	950	13	910	0.013	13,000	0.18	7,500	93%
13b	Miocene–Pliocene	10-13	3	6	11	6.4	47	2	8.4	41,799	20	26,000	22,000	48,000	530	560	13	520	0.012	7,000	0.17	4,300	46%
13c	Miocene–Pliocene		1	2	4	2.2	54	0	2.2	5,767	38	0	7,700	7,700	1,300	190	33	190	0.033	2,500	0.43	1,500	100%
13d	Miocene		0	1	3	1.3	90	0	1.3	63,233	2	0	4,500	4,500	71	110	2	110	0.0017	1,400	0.022	880	100%
14a	late Miocene–early Pliocene	14	2	4	13	6.0	70	2	8	21,721	37	2,100	21,000	23,000	970	520	24	480	0.022	6,500	0.30	4,000	91%
14b	**late Miocene–early Pliocene**	**5-6**	**1**	**2**	**3**	**1.9**	**43**	**2**	**3.9**	**9,284**	**42**	**150,000**	**69,000**	**220,000**	**7,400**	**2,000**	**220**	**440**	**0.047**	**24,000**	**2.6**	**8,900**	**32%**
14c	late Miocene–early Pliocene	6-9	3	5	8	5.1	39	3	8.1	24,048	34	12,000	17,000	29,000	710	440	18	390	0.016	5,400	0.22	3,400	58%
14d	late Miocene–early Pliocene	4	1	3	7	3.6	64	1	4.6	5,770	80	1,100	12,000	13,000	2,100	320	55	290	0.050	4,100	0.71	2,400	92%
15	Late Cretaceous–middle Eocene	45-61	1	2	11	4.3	89	1	5.3	83,204	6	950	15,000	16,000	180	360	4	340	0.0041	4,700	0.056	2,900	94%
16a,b	Permian	252-292	2	3	6	3.5	47	2	5.5	29,080	19	1,900	12,000	14,000	410	290	10	280	0.0096	3,800	0.13	2,300	87%
17	Cretaceous	118-137	3	6	12	6.7	51	0	6.7	77,511	9	0	23,000	23,000	300	560	7	550	0.0071	7,200	0.093	4,400	100%
18	Permian	252-292	1	2	4	2.2	54	0	2.2	17,765	12	0	7,500	7,500	420	190	11	170	0.0096	2,500	0.14	1,500	100%
19	Late Triassic–Middle Jurassic	200	0	1	4	1.6	97	0	1.6	45,642	4	0	5,900	5,900	130	150	3	140	0.0031	2,100	0.046	1,100	100%
20	Cretaceous		0	2	5	2.3	80	0	2.3	223,011	1	0	7,800	7,800	35	180	1	190	0.00085	2,500	0.011	1,500	100%
TOTALS						**145**		**69**	**214**	**1,200,000**		**590,000**	**750,000**	**1,300,000**		**20,000**		**13,000**		**250,000**		**130,000**	

[1]SA prefixes and PC suffixes have been removed from tract identification numbers to save space. [2]Age of the magmatic arc rocks hosting, or potentially hosting, porphyry copper deposits, and whose spatial distribution, projected to 1 km depth, defines the tract boundary. IUGS epochs and periods are from International Union of Geological Sciences (2000). [3]Consensus estimates of numbers of undiscovered deposits at the 90th, 50th, and 10th percentiles. [4]Calculated mean of consensus estimates of number of undiscovered deposits. [5]Calculated coefficient of variation, in percent. [6]Sum of number of discovered deposits and mean estimated undiscovered deposits. [7]Mean estimated mineralized rock containing the undiscovered metals. [8]Mean estimated undiscovered Cu as a percentage of the Cu endowment. Two significant digits are reported where appropriate. t=metric tons. **Results shown in bold are for tracts in which the giant porphyry copper deposit model was used**.

percent of the porphyry copper endowment is of Cenozoic age (table 3, fig. 3); the remainder is Cretaceous (4%), Jurassic (5%), and Permian (2%) in age. The Cenozoic endowment is in tracts with host rock ages of Eocene–Oligocene (39%), Miocene–Pliocene (29%), Paleocene–Eocene (12%), and Miocene (11%). The Eocene–Oligocene and Miocene–Pliocene tracts are dominated by giant tracts 10a,b and 14b, respectively.

In addition to copper, the undiscovered deposits also contain large estimated amounts of molybdenum (20,000,000 metric tons), gold (13,000 tons), and silver (250,000 tons). The estimated amounts of undiscovered copper in the Andes is equivalent to about 80 percent of the world reserve base; molybdenum, 105 percent; gold, 14 percent; and silver, 44 percent (fig. 4). The world reserve base is that part of the identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth.

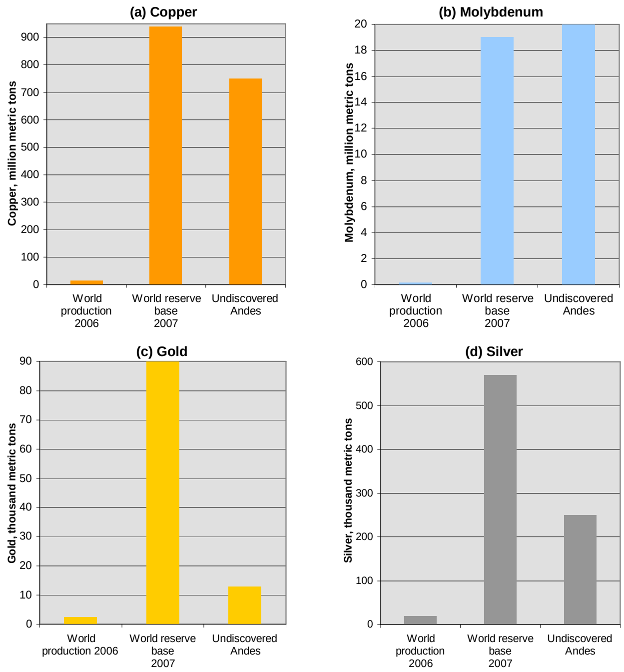

Figure 4 a-d. Column charts comparing world production (2006) and reserve base (2007) for (a) copper, (b) molybdenum, (c) gold, and (d) silver to the mean resources of these metals estimated in undiscovered porphyry copper deposits in the Andes. Production and reserve-base numbers are from Edelstein (2007), Magyar (2007), George (2007), and Brooks (2007), respectively.

Although Andean and world copper resources potentially are very large, unknown but probably large amounts are unavailable or restricted in ways that discourage discovery and development and (or) increase cost. The cost of copper is of growing concern. Copper prices increased about 470 percent between 2002 and 2007. One reason copper resources are limited is because a large amount of land permissive or even favorable for the occurrence of undiscovered mineral deposits is unavailable or restricted for mineral exploration, discovery, and development because these lands include urban areas, transportation corridors, forest and wildlife preserves, scenic natural areas, sensitive ecosystems, protected biodiversity areas, sensitive and threatened surface and groundwater supplies, wilderness areas, national parks, and private land where mining is not desired. In the western United.
States, for example, Hyndman et al. (1991) found that about 55 percent of the 2.1 million square kilometers of Federal mineral estate they studied was severely restricted or unavailable for mineral exploration and development; only 23 percent was available without restrictions. How much of the 1.2 million km^2 of land permissive for the occurrence of undiscovered porphyry copper deposits in the Andes is available for mineral exploration, discovery, and development?

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