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Quantification of undiscovered mineral-resource assessment -- The case study of U. S. Forest Service wilderness tracts in the Pacific Mountain System

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Introduction

During the last decade, resource-assessment techniques for oil and gas have developed to the point where future rates of discovery can be forecast with some confidence in geographic areas that are only moderately well-explored. The development of techniques for the quantitative assessment of metallic mineral resources, however, has progressed more slowly. There are many reasons for this apparent lack of progress. One reason is that the geology and geochemistry of mineral deposits are far more complex than those of oil and gas deposits. In addition, statistics on the exploration for and discovery of mineral deposits are very poorly recorded compared to the massive efforts made by the petroleum industry and governments to track the detailed history of exploration and production and to record the size of each hydrocarbon discovery. Mineral exploration's role as a "potential leading indicator of mineral development and supply" has prompted recommendations that more emphasis be given to collecting comparable quantitative data on exploration activities and resulting discoveries (National Research Council, 1982, p. 114-125).

Acknowledging this state of affairs, mineral-resource assessment might be abandoned in favor of other tasks that are perceived as more worthwhile. A number of recent publications suggest, however, that progress is possible. A method of regional mineral-resource assessment based on the size distribution of mineral deposits of specified geologic types and on the probability of deposit occurrence was proposed by Singer (1975) and applied by the U. S. Geological Survey (USGS) to areas in Alaska. Subsequent applications of this assessment method by the USGS in Alaska, in the conterminous 48 states, and in other countries, have resulted in the construction of a large number of descriptive models of mineral deposit types (Cox, 1983a,b) and of associated numerical grade and tonnage models (Singer and Mosier, 1983a,b). In addition, the procedures for the grade-tonnage-model approach to regional mineral-resource assessment have been presented in schematic flow diagrams by Hodges and others (1983). Using the results (subjective estimates of number of deposits and copper-deposit grade and tonnage distributions) of USGS resource assessments in Alaska, Charles River Associates (1978, p. 2-39 to 2-47) attempted to estimate the copper endowment of Alaska.

The application of these resource-assessment techniques were being developed at the same time that the USGS and the U. S. Bureau of Mines (USBM) were completing a 20-year program to determine the mineral potential of the U. S. Forest Service wilderness areas. In 1984, a summary of subjective evaluations of nearly 800 tracts of wilderness land were published in the two-volume, 1183-page, USGS Professional Paper 1300 (Marsh and others, 1984). This publication and studies referenced in it document site-specific information about the mineral resources of designated wilderness, roadless, or study areas in 31 states.

The studies cited above provide three elements needed to produce a quantitative estimate of the amount of a mineral resource in an area: (1) a conceptual framework for resource assessment, (2) a number of numerical grade-tonnage models for geologic deposit types, and (3) a subjective assessment of the favorability for occurrence of mineral resources which is based on geology, geochemistry, and geophysics. Although previous studies (for example, Richter, Singer, and Cox, 1975) present estimates of undiscovered deposits of specified geologic types and data on the grade and tonnage distributions for those types of deposits, few attempts have been made to estimate an area's undiscovered metal endowment.[1/] For instance, the Charles River Associates (1978) study, mentioned earlier, includes only the copper in porphyry-copper-type deposits when calculating the copper endowment of four areas in Alaska assessed by the USGS,[2/] although the Charles River study explains how the USGS data for other (mafic volcanogenic massive sulfide, felsic and intermediate volcanogenic massive sulfide, and copper skarn or contact metamorphic) deposits could be used to calculate additional copper to add to the endowment total for Alaska.

This study produces an aggregate assessment of an area's undiscovered metal endowment for not just one metal contained in one deposit type, but for eleven metals contained in 14 deposit types.[3/] This area considered in this case study is 91 Forest Service wilderness tracts in a region called the Pacific Mountain System. The tracts, shown in figure 1, are located in California, Nevada, Oregon, and Washington.

Figure 1 near here

The assessment of undiscovered metal endowment in this study is based on the conceptual framework of geologic deposit models, fulfilling the first

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1/ Undiscovered metal endowment (or more simply, endowment, in this report) refers to metal contained in undiscovered deposits of the deposit types considered in the investigation, and which are predicted to exist in the area studied.

2/ These studies are described in Singer and Ovenshine (1979). The four areas studied were the Brooks Range (Grybeck and DeYoung, 1978), the Seward Peninsula (Hudson and DeYoung, 1978), Central Alaska (Eberlein and Menzie, 1978), and southern Alaska (MacKevett and others, 1978).

3/ As shown later in this paper, more than 14 deposit types were considered in this study, but grade and tonnage models were not available for some types and no undiscovered deposits were estimated for some other types.

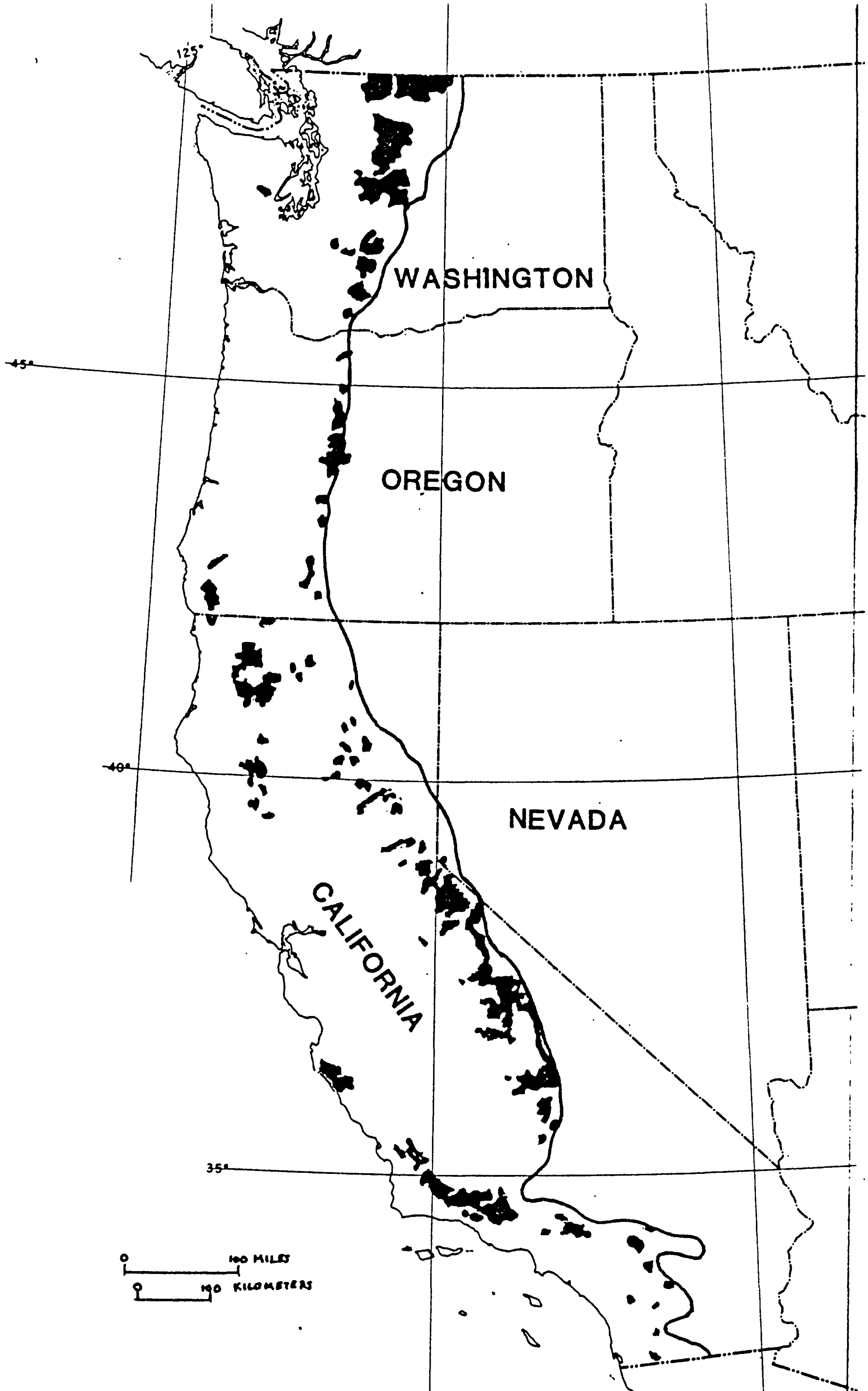

Figure 1.--Location of U. S. Forest Service wilderness tracts in the Pacific Mountain System.

element needed for a quantitative assessment. The endowment for any metal is calculated by summing the products of the estimates of the number of undiscovered deposits for each type containing the metal times the amount of metal contained in that type of deposit (tonnage times grade for that metal). This calculation requires the second and third elements of a quantitative assessment: numerical grade-tonnage models for the deposit types listed in table 1, and subjective estimates of the number of undiscovered deposits, which were made by a team of

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Table 1 near here

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economic geologists. These estimates of the number of undiscovered deposits embody the degree of favorability for deposit occurrence as well as the sizes of the tracts of land assessed. The estimates were supported, when possible, by analysis of deposit-occurrence density in well-explored areas, using methods similar to those explained by Page and Johnson (1977) in their study of podiform chromite deposits. Finally, a method for combining the estimates of deposit number and their size and grades into an estimate of contained metal is needed. In order to incorporate the uncertainty reflected in the frequency distributions of number of deposits and in the deposit grade-tonnage models, the technique of computer simulation was selected to enable the confluence of method, requisite numerical models, and subjective estimates of deposit occurrence to produce hither to unattainable insights into the unknown.

The approach used for this resource assessment has several qualifications.

- The estimates of metal endowment only include the 11 metals evaluated for the first 14 deposit types listed in table 1. For several of these metals, including chromium, lead, manganese, nickel, and zinc, there are more important deposit types in terms of world resources than those types in table 1. Grade-tonnage models were not available; however, the area of the study was not favorable for occurrence for most of them. Other metals, such

Table 1.--Number of deposits by deposit type, which were considered in the assessment of undiscovered metal endowment of U. S. Forest Service wilderness tracts in the Pacific Mountain System.

Deposit type 1/	Metals or minerals contained 2/	Reference for grade-tonnage model 3/	Expected number of undiscovered deposits
Porphyry copper	Cu, Mo, Au, (Ag)	a - 21	3.5
Massive sulfide in felsic and intermediate volcanic rocks (Medford type)	Cu, Zn, Au, Ag, (Pb)	c	5.5
Low-sulfide quartz-gold (Medford type)	Au	c	7.5
Low-sulfide quartz-gold (Mother Lode type)	Au, (Ag)	b - 54	4.2
Podiform chromite (California type)	Cr	a - 3	162.5
Silica-carbonate mercury	Hg	b - 59	5
Subaerial volcanogenic manganese	Mn, (P)	b - 65	1
Hot springs mercury	Hg	b - 62	0.5
Tungsten skarn	W	a - 49	2.0
Epithermal gold, quartz-adularia type (Nevada-California type)	Au, Ag	c	2.1
Copper skarn	Cu, (Au, Ag)	a - 38	0.1
Synorogenic synvolcanic nickel	Cu, Ni, (Co, Pd, Pt, Au)	b - 7	0.1
Zinc-lead skarn	Cu, Zn, Pb, Ag	b - 26	1.5
Molybdenum porphyry (low fluorine type)	Mo	a - 31	0.5
Placer gold	Au	none	(4)
Buried Tertiary placers	Au	none	(4)
Massive sulfide, Cyprus type	Cu, (Zn, Pb, Au, Ag)	a - 52	none
Sediment-hosted submarine exhalative zinc-lead	Zn, Pb, Ag	a - 69	none
Red-bed/green-bed copper	Cu Ag	none	none
Chrysotile asbestos	Asbestos	b - 23	none
Nickel laterite	Ni, (Co)	b - 95	none 5/

1/ Descriptive models corresponding to most of these deposit types are in Cox (1983a,b).

2/ Metals in parentheses were not included in the determination of undiscovered metal endowment for this study as they are mostly potential by-products and grade data were not available for all the deposits used to construct the gradetonnage models. In the case of subaerial volcanogenic manganese deposits, phosphorous is important as an impurity and not as a resource.

3/ Reference to publication source (and, where appropriate, page number) of grade-tonnage model. Key: a, Singer and Mosier (1983a); b, Singer and Mosier (1983b); c, Singer and others (1983).

4/ Number of deposits not estimated.

5/ No undiscovered deposits expected although identified deposits occur in the study area.

as aluminum, cobalt, iron, tin and titanium were not included in the aggregate metal totals as there were no favorable tracts for deposit types containing these metals. The amounts of industrial minerals such as phosphate, potash, and sulfur and of the more common mineral construction materials like building stone, cement rock, and sand and gravel, have also been omitted from this study.

o The study is confined not only to deposits of the types specified, but also to only the undiscovered resources that occur in those deposit types. Some of the wilderness tracts contain deposits that have been drilled and for which estimates of tonnage and grade are publically available. These estimates are presented in Marsh and others (1984) and have not been included in this case study.

o The existence of undiscovered deposits can be postulated in various economic classes (USBM and USGS, 1980), but in this report the mineral endowment in undiscovered deposits is assessed without regard to economic rating of the deposits.

o Resource assessments are based on the present knowledge about science, technology, and economics. A change in scientific knowledge, such as the recognition of a geologic deposit type that was not known before or the application of new geologic theories of mineral-deposit genesis, may necessitate major changes to a resource assessment. In a similar fashion, changes in the technology available to explore for mineral deposits and to produce metals from deposits having specified depth, location, mineralogy, grain size, and grade can change the definitions or deposit models used in the resource assessment. Finally the economics of the metal industries, including the supply and demand situation for by-products and substitute materials can transform today's mineralogical curiosity into tomorrow's ore deposit -- or vice versa.

o Because the economics of undiscovered resources are not considered (except in the implicit sense of basing the analysis on grade-tonnage models constructed with data from deposits that have been examined with the intent of production), conclusions are not drawn in this paper regarding the costs, probability, and time required to find the undiscovered deposits and the costs and time required to produce metal(s) from the deposits. To extend the resource assessment to these topics, modelling of the exploration or search process, engineering analysis of costs of exploration, mining and processing costs studies, and market analysis would be required. Some of the metals assessed are potential by-products, such as gold in porphyry copper deposits; by-product production would be dependent on the production of main product (copper and possibly molybdenum in the case of porphyry deposits) and might be spread over a mine life of perhaps 30 to 50 years.

Analytic Procedure

The analytic procedure used consists of three steps:

1. Inspection of the detailed USGS/USBM reports for each of the 91 wilderness tracts by the team of economic geologists.
2. Estimation of the expected number of undiscovered deposits by type in each wilderness tract or in groups of wilderness tracts.
3. Use of computer simulation to estimate the aggregate quantity of metal expected to be contained in these undiscovered deposits.

In order to complete the first step efficiently, the Pacific Mountain System was partitioned into four regions: Cascade region, Klamath Mountains region, Sierra Nevada and Foothills region, and southern California region. Then the detailed USGS/USBM reports for the wilderness tracts within each of the four regions were studied by one of the economic geologists on the team.

The second step, a presentation of the findings of this study to the entire team, included an interpretation of the favorable and unfavorable indications of mineral-deposit occurrence, followed by a question and answer period when the other team members determined the soundness of the interpretation. The identification of the types of mineral deposits that could occur was followed by an estimate of the number of deposits of each type expected to occur in each area. The favorable and unfavorable indications of mineral-deposit occurrence included geologic and tectonic terranes, existing mineral deposits and occurrences, altered rocks, geochemical anomalies, cover of favorable terranes by unfavorable rocks, and the extent and adequacy of exploration. For example, copper-lead-zinc stream-sediment anomalies in terranes containing subaerial andesitic to rhyodacitic volcanic rocks with minor occurrences of pyritic massive sulfide deposits, and negative aeromagnetic anomalies (an indication of hydrothermal alteration) were considered to be positive evidence of undiscovered massive sulfide deposits of the Medford type. In some areas only a few of the criteria were known and estimates were lowered. In most instances, a consensus estimate was established quickly; in others, more discussion was required.

The third step in the analysis was to use Monte Carlo simulation to estimate the expected quantities of metal contained in the area of the 91 wilderness tracts studied. The simulation process was designed to make the estimates of metal endowment unconditional; that is, these estimates were made in such a way that the range of possibilities for each tract varied from the chance of no deposits occurring up to n deposits occurring. As a result, the computed metal distribution percentiles reflect variations which arise from both the uncertainty of deposit occurrence and variation of grade and tonnage.

A schematic diagram of the estimation process is shown in figure 2. The

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Figure 2 near here

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estimates of the number of deposits expected to occur in each area ($E(N_{ij})$) along with the estimated parameters of the grade and tonnage models are the basic inputs into the simulation procedure. The first distribution to be sampled in the computer simulation is a Poisson distribution used to obtain an estimate of the number of deposits of type i occurring in area j on simulation cycle k. The tonnage distribution for deposit type i is sampled next to obtain a tonnage for this deposit type on simulation cycle k. The associated grade distributions are sampled next to obtain grade estimates G_{ik}^{P}, $G_{ik}^{S_1}$, ..., $G_{ik}^{S_n}$. Any known correlations between grade and tonnage are taken into account when sampling the grade distributions. In a number of cases, contained-metal models are used in place of grade and tonnage models.

The expected quantity of metal for the current simulation cycle is then computed ($M_m(k)$, where m is the index of the metal and k is the index of the simulation cycle). The simulation process is then repeated to build the metal distributions from which mean, median, and confidence intervals are in turn computed.

Types of undiscovered deposits expected to occur

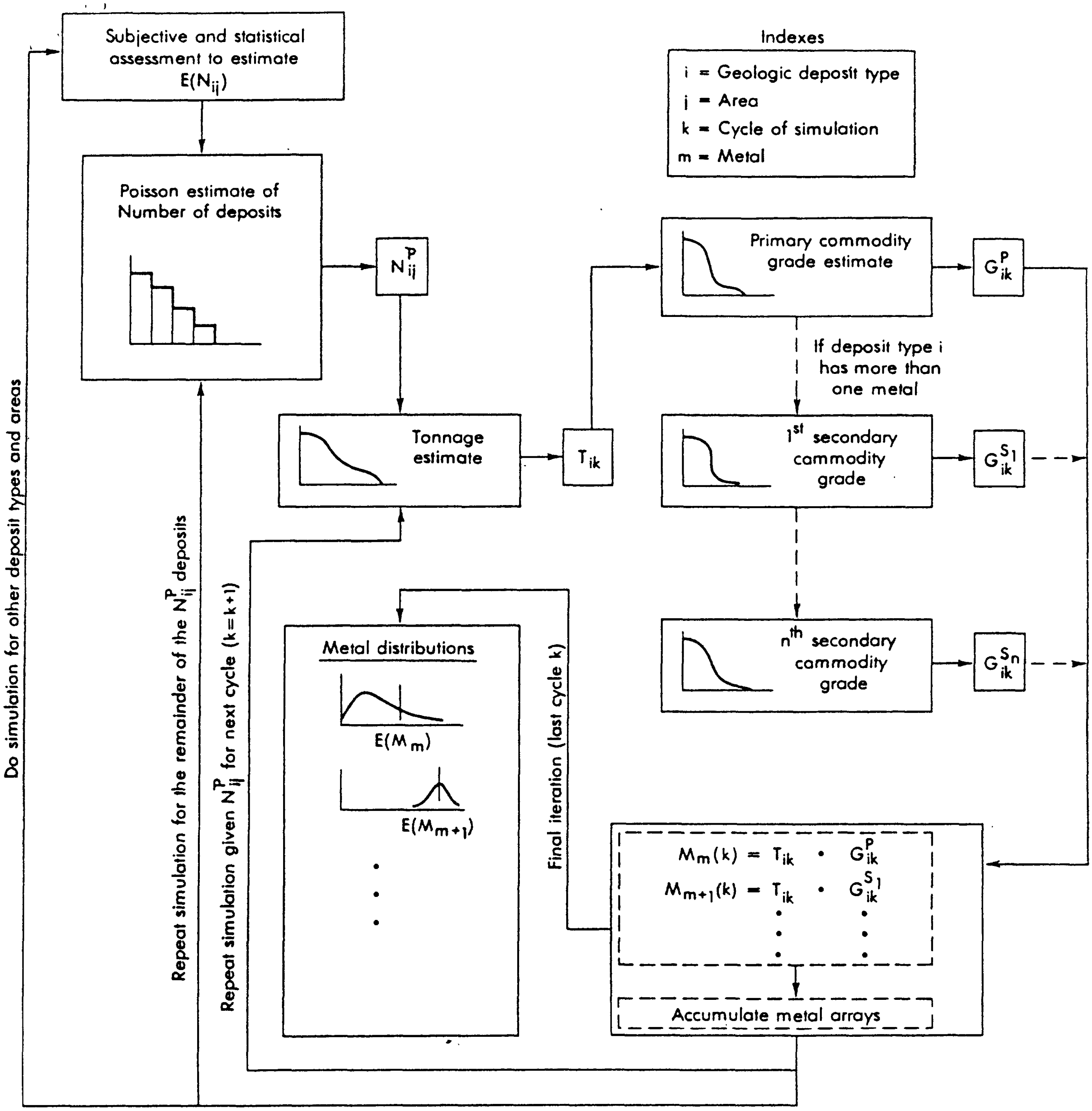
Some undiscovered deposits were estimated to occur in 52 of the 91 wilderness tracts studied. As discussed earlier, deposits that have been sufficiently explored to have an assigned tonnage and grade estimate were excluded from this group of undiscovered deposits; however, identified deposits whose subsurface

Table 2.--Estimates of undiscovered metal endowment of the U. S. Forest Service wilderness tracts in the Pacific Mountain System.

(in thousand metric tons of metal or oxide)

Metal or oxide	Median undiscovered metal endowment	Upper and lower deciles		Mean endowment	E/C Ratio 1/
		90%	10%		
Chromic oxide (Cr_2O_3)	60	40	100	68	0.1
Copper	5700	850	23000	10000	2.6
Gold	0.15	0.038	0.63	0.30	1.2
Lead	110	0	1700	880	0.1
Manganese	7.6	0	350	180	0.01
Mercury	2.7	0.27	20	11	1.3
Molybdenum	220	25	1100	460	8.5
Nickel	0	0	0	7.0	0
Silver	1.6	0.25	9.2	4.5	0.4
Tungsten (WO_3)	23	0	400	220	2.0
Zinc	640	89	3400	1700	0.7

1/ Ratio of median undiscovered metal endowment (column 2) to average U. S. apparent consumption for the years 1979-82 (from U. S. Bureau of Mines, 1984).



$E(N_{ij})$ = Expected number of deposits of type i in area j

N^P_{ij} = Number of deposits of type i in area j computed from a Poisson distribution

T_{ik} = Tonnage for model type i on cycle k

G^P_{ik} = Grade for the primary commodity in model type i on cycle k

$G^{S_1}_{ik}$ = Grade for the 1st secondary commodity in model type i on cycle k

$M_m(k)$ = Expected quantity of metal m generated on cycle k

$E(M_m)$ = Expected quantity of metal m in all areas

Figure 2.--Computer simulation model to estimate undiscovered metal endowment.

extent was unknown were included in this assessment. Individual areas merited consideration of as many as seven deposit types, though one or two was most common. Table 1 lists the 21 mineral deposit types considered in this assessment and estimates of the number of deposits expected for 14 of these deposit types.

By far the largest expected number of undiscovered mineral deposits predicted for any one type is 162.5 for podiform chromite deposits. This large number of chromite deposits far exceeds the second largest expected number, 7.5 for Medford-type low-sulfide quartz-gold deposits. Development of subsurface exploration techniques would be required to find these podiform chromite deposits, because of the depths at which they occur. Most, if not all, podiform chromite deposits occurring at the surface in the area studied have been discovered. In this resource assessment, estimates of the number of deposits were made for those occurring down to a depth of 200 m, based on the study of Page and Johnson (1977), who investigated the distribution of podiform chromite deposits within areas underlain by ultramafic rocks in the Medford-Coos Bay quadrangle, southwestern Oregon. They found that an average of 0.2 deposits occurred per square kilometer to a depth of 200 m and inferred by the distribution of deposits with respect to topography that podiform chromite deposits would have a similar distribution in the subsurface.

The largest tonnage deposits expected to occur are porphyry copper deposits (3.5 deposits expected), which contain most of the copper and molybdenum of this assessment and a substantial portion of the gold. Another contributor to the gold total is quartz-adularia gold deposits (2.1 deposits expected), which are epithermal vein deposits (containing up to about 20 metric tons of gold and 1000 tons of silver) with high gold and silver grades. These deposits are found in a common type of altered rock; however, not all areas with alteration contain deposits, and, for those that do, the deposits are small relative to the altered area and may be difficult to locate. Another source of gold in this assessment is low-sulfide vein deposits of the Mother Lode and Medford types. Undiscovered deposits of these types probably are not exposed; however, deposits may occur beneath younger covering units or at depth within metamorphic host rocks.

Three types of skarn, or contact metamorphic, deposits are predicted to be among the undiscovered resources of the wilderness tracts studied. They are tungsten skarn deposits (the only deposits contributing tungsten to the undiscovered resource totals in the study), copper skarn deposits, and zinc-lead skarn deposits. The tungsten skarn deposits are associated with roof pendants in granitoid rocks. Undiscovered tungsten skarn deposits in this area are not likely to be exposed and because of their characteristics would be difficult to discover.

Small quantities of gold, silver, copper, and zinc are attributed to undiscovered volcanogenic massive sulfide deposits of Mesozoic age (5.5 deposits expected). Mercury is expected to occur in silica-carbonate deposits (5 expected) and hot springs deposits (0.5 expected). Manganese is in small-tonnage volcanogenic deposits associated with chert within the Franciscan formation in California (one deposit expected). Small quantities of molybdenum are from one area that was identified as favorable for the occurrence of low-fluorine molybdenum porphyry deposits (0.5 deposits expected). Nickel was also expected in one area (0.1 deposit expected of the synorogenic type). Brief descriptions and grade and tonnage distributions for the deposit types in table 1 can be found in Cox 1983a,b; Singer and Mosier, 1983a,b; and Singer and others, 1983.

Tonnage of metal in predicted undiscovered deposits

The 14 deposit types mentioned above contribute to the undiscovered resource estimates for 11 metals. As shown in table 1, two of the deposit types, massive sulfide deposits of the Medford type and zinc-lead skarn deposits, include four metals each that are included in the resource estimates. On the other hand, nine of the 14 deposit types are the source of only one metal in the analysis. The metal totals that include amounts from the most deposit types, five, are for copper and gold. Totals for five of the metals assessed (chromium, lead, manganese, nickel, and tungsten) are drawn from only one deposit type each.

The statistics describing the aggregate distribution for each metal predicted to occur in undiscovered deposits are in table 2. These statistics included

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Table 2 near here

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the mean, median, the 90th and 10th percentiles and a statistic defined as the median endowment to consumption index (E/C ratio). The denominator of this index is the 1982 U.S. consumption for each commodity.[4/] The median is reported as the primary measure of the central tendency of each metal distribution because of the large skewness in all but one of these distributions. Only for the chromic oxide distribution is the mean a good measure of the "middle" of the distribution. This is a result of the near normality of the grade distibution for podiform chromite deposits (the only deposit type contributing to the chromic oxide total) and the large number of these deposits estimated to occur. Each of the other grade and tonnage and contained metal distributions display large positive skewness. The median and both percentile estimates for the nickel endowment are zero. This is because of the large uncertainty that any deposits occur which contain nickel.

4/ The measure of U. S. consumption used was the average of apparent consumption for the 4-year period 1979-82 as calculated from data reported by the U. S. Bureau of Mines (1984). Apparent consumption is generally defined as U. S. primary and secondary production plus net import reliance.

The statement that the median estimate of the undiscovered copper endowment of the study area is 5.7 million metric tons means that, based on the above analysis, if one had many regions having the same geologic characteristics as the total of the Pacific Mountain System wilderness tracts, one would expect, all other things being equal, that 50 percent the regions would contain more than this number of tons and 50 percent of the regions would contain less. Ninety percent of the regions would contain at least 847 thousand metric tons of copper in undiscovered deposits and 10 percent of the regions would contain 22.8 million metric tons or more. Another statement that can be made is that for 80 percent of such regions, the undiscovered endowment of copper is between 847 thousand and 22.8 million metric tons with 5.7 million metric tons being the best single point estimate of the undiscovered endowment. As a reference, this median estimate of 5.7 million metric tons represents about 2.6 years of U.S. consumption at the 1979-82 level. This E/C index should only be taken as a qualitative reference.

Conclusions

The ultimate goal of mineral-resource assessment is to obtain an estimate of the value of the mineral resource to use in planning for mineral exploration, land-use, and mineral availability. The techniques described in this paper form a foundation, but only partially achieve the objective of such an estimate. Although the results presented here bridge a gap between qualitative assessment of an area's favorability for mineral deposit occurrence and a mineral commodity inventory for the area, the method used here is based on the physical occurrence of mineral deposits and does not explicitly consider the economic processes of exploration, development, production, processing, and marketing that transform a mineral resource into a material product. The improvement represented by the techniques presented in this paper is that models of such economic processes can now be applied to an appropriate data set -- expected numbers, tonnages, and grades of deposits.

The analysis for this case study suggests several ways that an improved quantitative estimate of mineral resources can be made. Using the techniques employed for this assessment, improvements in several areas are possible. First, more geologic observations relevant to the occurrence of specified deposit types could be collected. Second, more data could be sought on the density of mineral-deposit occurrence by deposit type (if possible, conditioned on geologic features). Third, grade-tonnage models could be improved by adding more observations to existing models and by constructing models for additional deposit types. Finally, the quest for a quantitative estimate of an area's mineral resources could be extended beyond the methods used in this case study to include identified as well as undiscovered resources and to incorporate exploration and production models with the occurrence estimates for each deposit type.

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