Is There a Metric for Mineral Deposit Occurrence Probabilities?

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Traditionally, mineral resource assessments have been used to estimate the physical inventory of critical and strategic mineral commodities that occur in pieces of land and to assess the consequences of supply disruptions of these commodities. More recently, these assessments have been used to estimate the undiscovered mineral wealth in such pieces of land to assess the opportunity cost of using the land for purposes other than mineral production. The field of mineral resource assessment is an interdisciplinary field that draws elements from the disciplines of geology, economic geology (descriptive models), statistics and management science (grade and tonnage models), mineral economics, and operations research (computer simulation models). The purpose of this study is to assert that an occurrence-probability metric exists that is useful in "filling out" an assessment both for areas in which only a trivial probability exists that a new mining district could be present and for areas where nontrivial probabilities exist for such districts.

Key words:
Mineral resources
Assessment
Occurrence probabilities
Denudation rates

Introduction

Regional mineral resource assessments can be either qualitative or quantitative summations of the identified and undiscovered mineral resources of pieces of land. In the past these assessments were primarily performed to estimate the inventory of mineral resources as a basis for evaluating the adequacy of future supply of mineral commodities. For many years the so-called "critical and strategic" commodities, such as chromium, cobalt, and manganese, were of particular concern. These older assessments often contained quantitative statements about identified resources and qualitative statements about the magnitude of undiscovered resources. More recently, resource assessments have been performed to help classify public lands. In many cases the primary concern in these decisions related to undiscovered resources. Qualitative mineral resource assessments were not explicit enough to meet the needs of policymakers, who were required to estimate the opportunity cost of not producing the mineral commodities from undiscovered mineral deposits when land is to be used exclusively for recreation or wilderness. The needs of policymakers for more explicit statements about the magnitude of undiscovered mineral resources present led to the development of quantitative methods of mineral resource assessment. Quantitative mineral resource assessments are estimates of the quality and quantity of the undiscovered mineral wealth located in particular areas.

The shift toward quantification has required the development of tools that characterize important properties of mineral deposits, criteria to estimate mineral deposit occurrence probabilities, and methods to summarize the amounts of undiscovered minerals. Specifically, these tools include descriptive mineral deposit models that provide criteria to delineate areas permissive for mineral deposit occurrence, grade and tonnage models, procedures to estimate the number of undiscovered mineral deposits, and computer simulation procedures to compute the total quantity of each type of metal that occurred in different types of mineral deposits that may be assessed in the study area.

The purpose of this article is to examine mineral resource assessment from a broad framework of geological processes and products to see whether such a view can provide the basis for developing metrics, or measures, that are useful for estimating the probabilities of occurrence of different types of mineral deposits in geological entities. We also briefly explore how these metrics relate to present mineral deposit models (Cox and Singer, 1986) to establish a basis for calibrating the measures developed. Magmatic arcs and resulting volcano-plutonic complexes are used as examples for examining this approach.

In this article we briefly examine (1) the sizes of volcano-plutonic complexes, (2) the level of denudation of the volcano-plutonic complex, and (3) the number and character of intrusive centers in a complex as bases for developing metrics for probability of occurrence of different types of mineral deposits.

In examining intrusive centers, we will use concepts from linear algebra to investigate systematic linkages between the occurrence probabilities for various types of mineral deposits that may occur around these centers. For deposits associated with intrusive centers, porphyry deposits and their kin deposits—polymetallic veins, skarns, and polymetallic replacement deposits, these linkages are positive (positive spatial correlation). However, we suggest that these same algebraic concepts can be used to represent linkages between deposits that are mutually exclusive, and between deposit types that may be characterized as facies equivalents, that is, show a positive-lagged spatial correlation.

Sizes of Volcano-plutonic Complexes and Probability of Mineral Deposit Occurrence

One of the tools that has been used to estimate the number of undiscovered deposits of a particular type that may occur within a region is spatial mineral deposit models. As described by Bliss and Menzie (in press), these models consist of two parts: (1) a mineral-deposit density, or probability that a deposit of a particular type occurs within some standard measured (control) area, and (2) a discrete distribution that describes the pattern of deposits within the control area. A critical requirement for developing a mineral-deposit density is the definition of rules for identifying control areas. These rules must be based upon geological features that are broadly related to the deposits and that may be recognized in regional geological, geochemical, and geophysical studies.

If we are assessing a calc-alkaline, volcano-plutonic complex of subaerially deposited andesites and associated quartz monzonite intrusions, we must consider at least the list of deposits in table 1. A mineral-deposit density for the deposit types related to the volcanic rocks can be developed by determining the number of deposits of each of these seven types that occur within well-explored volcanic sequences. Similarly, mineral-deposit density models of those types of deposits associated with the intrusive parts of volcano-plutonic complexes can be developed by counting the number of deposits of each of the five types of deposits that occur within or adjacent to the intrusive "roots" of the complex. The resulting mineral-deposit density could then be used together with

Table 1. Candidate deposit types for a calc-alkaline volcano-plutonic complex.

Model number	Title
Deposit types related to the volcanic rocks	
25a	Hot-spring Au-Ag (Berger, 1986a)
25b	Creede epithermal veins (Mosier, Sato, and others, 1986)
25c	Comstock epithermal veins (Mosier, Singer, and Berger, 1986)
25d	Sado epithermal veins (Mosier, Berger, and Singer, 1986)
25e	Epithermal quartz-alunite Au (Berger, 1986b)
25g	Epithermal Mn (Mosier, 1986)
27a	Hot-spring Hg (Rytuba, 1986)
Deposit types related to the intrusive rocks	
20c	Porphyry Cu-Au (Cox, 1986d)
21a	Porphyry Cu-Mo (Cox, 1986e)
18a	Porphyry-Cu-skarn-related (Cox, 1986b)
19a	Polymetallic replacement (Morris, 1986)
22c	Polymetallic veins (Cox, 1986c)

regional geophysical surveys to estimate the endowment of deposits associated with concealed intrusions.

Spanski and others (1991) used this approach to estimate the number of undiscovered porphyry copper deposits in the Cascades geologic province. The keys to that assessment were (1) the development of a local mineral-deposit density model for part of the region, and (2) the recognition of a geophysical signature that was believed to be related to intrusive parts of a large volcano-plutonic complex (Blakely and Plouff, 1991). These geophysical anomalies show a variety of sizes and shapes that may reflect both along arc (elongate anomalies) and cross arc features (equant anomalies). Lengths of the elongate anomalies, 50 to 150 km, are similar to the lengths of some plutons with known, related porphyry copper deposits (table 2). Each of the intrusions in table 2 contains at least one porphyry copper deposit. It is reasonable to suggest that 10 porphyry copper deposits represents an upper limit on the number of porphyry deposits associated with such an intrusion. Therefore, the mineral deposit density for such intrusions, prior to significant erosion, may lie in the range of .000x to .00x deposits per square kilometer of intrusion.

Level of Denudation and Probability of Mineral Deposit Occurrence

Consider a region underlain by a calc-alkaline, volcano-plutonic complex of subaerially deposited andesites and associated quartz monzonite intrusions that must be assessed for its undiscovered mineral resources as part of a land classification decision. The first step in assessing the region is to compile a list of candidate deposit types that might occur within the region (table 1). Whereas the geological setting (a subaerial, calc-alkaline volcano-plutonic complex) permits the presence of all of these deposit types, only some of the types will be assessed, depending upon three factors: (1) the depth that is chosen as a cutoff for the assessment, (2) the degree to which the volcano-plutonic complex has been eroded, and (3) the environment into which the intrusion is emplaced. This selective applicability of deposit types in an assessment is a consequence of genetic processes that act at particular depths and in different settings (wall rock and structure) in the complex.

Figure 1 shows two porphyry intrusions emplaced at relatively shallow crustal levels. The porphyry on the right is emplaced into comagmatic volcanic rocks, where-

Table 2. Sizes of some plutonic complexes that host porphyry copper deposits.

Pluton	Length of pluton (km)	Width of pluton (km)	Reference
Boulder Batholith, Montana	100	30	Meyer and others (1968)
Guichon Batholith, British Columbia	80	32	McMillan (1976)
Babine Intrusions, British Columbia	106	45	Carter (1976)

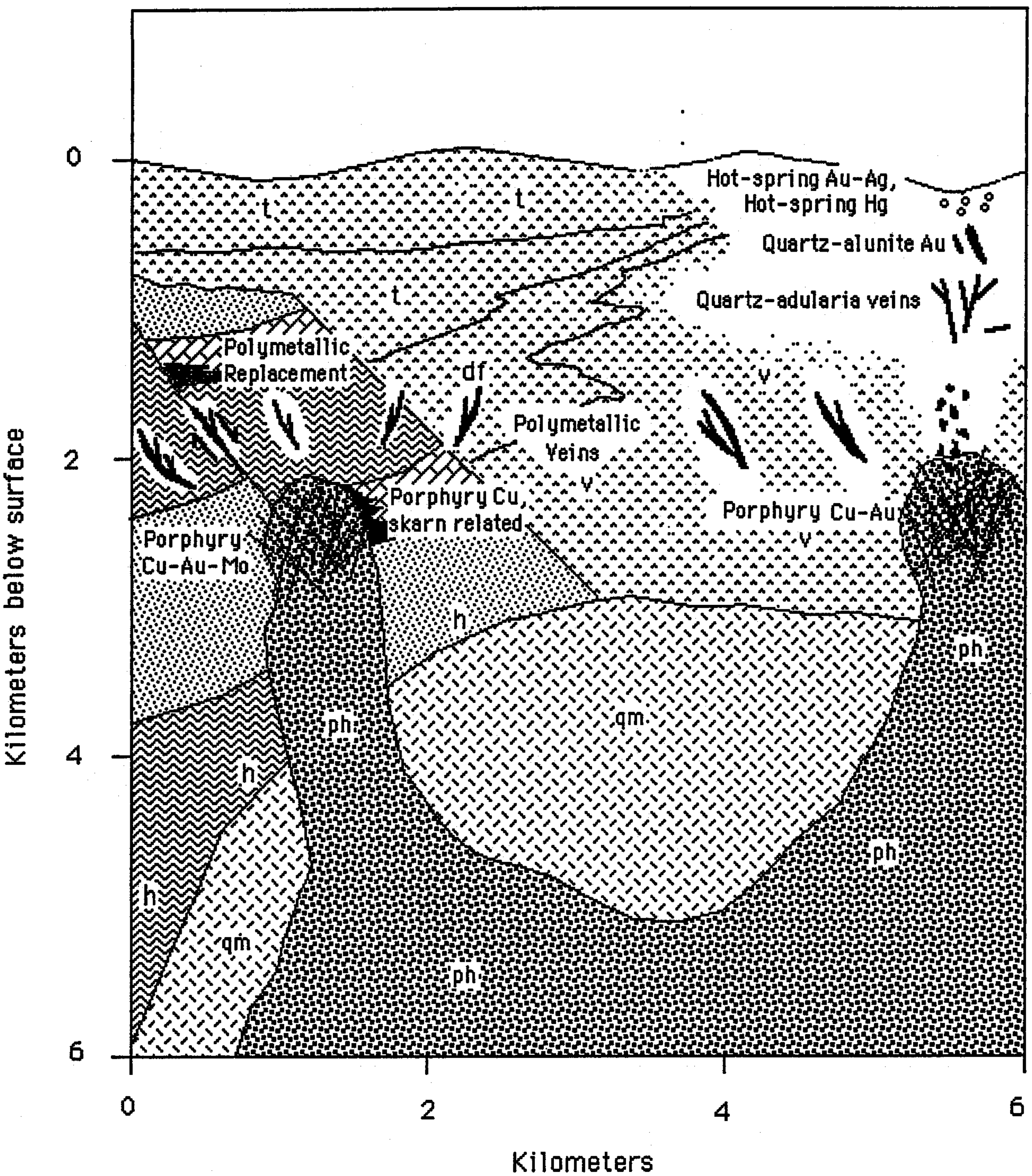

Figure 1. Porphyry-Cu-type intrusion emplaced at shallow crustal levels. qm, quartz monzonite; ph, porphyry; v, volcanic flows; df, debris flows; s, volcanoclastic sediments; t, tuffs; h, hornfels; [carbonate symbol], carbonate; [sandstone symbol], sandstone; [shale symbol], shale.

as the porphyry on the left was emplaced into older sedimentary rocks adjacent to the volcano-plutonic complex. In this figure, the volcano-plutonic complex is only slightly eroded, and it is unlikely that the deposit types in table 1 that are identified as related to the intrusive rocks will occur within the depth cutoff of the assessment. If the complex has undergone significant erosion, it is unlikely that deposit types in table 1 that are identified as related to volcanic rocks will be preserved. Figure 2 shows a porphyry intrusion emplaced at deeper crustal levels; again the level to which the complex has been eroded and the depth cutoff of the assessment will affect the deposit types that are assessed.

The problem for the resource assessor is to determine to what depth the area being assessed has been eroded, and at what depths relative to the present erosional sur-

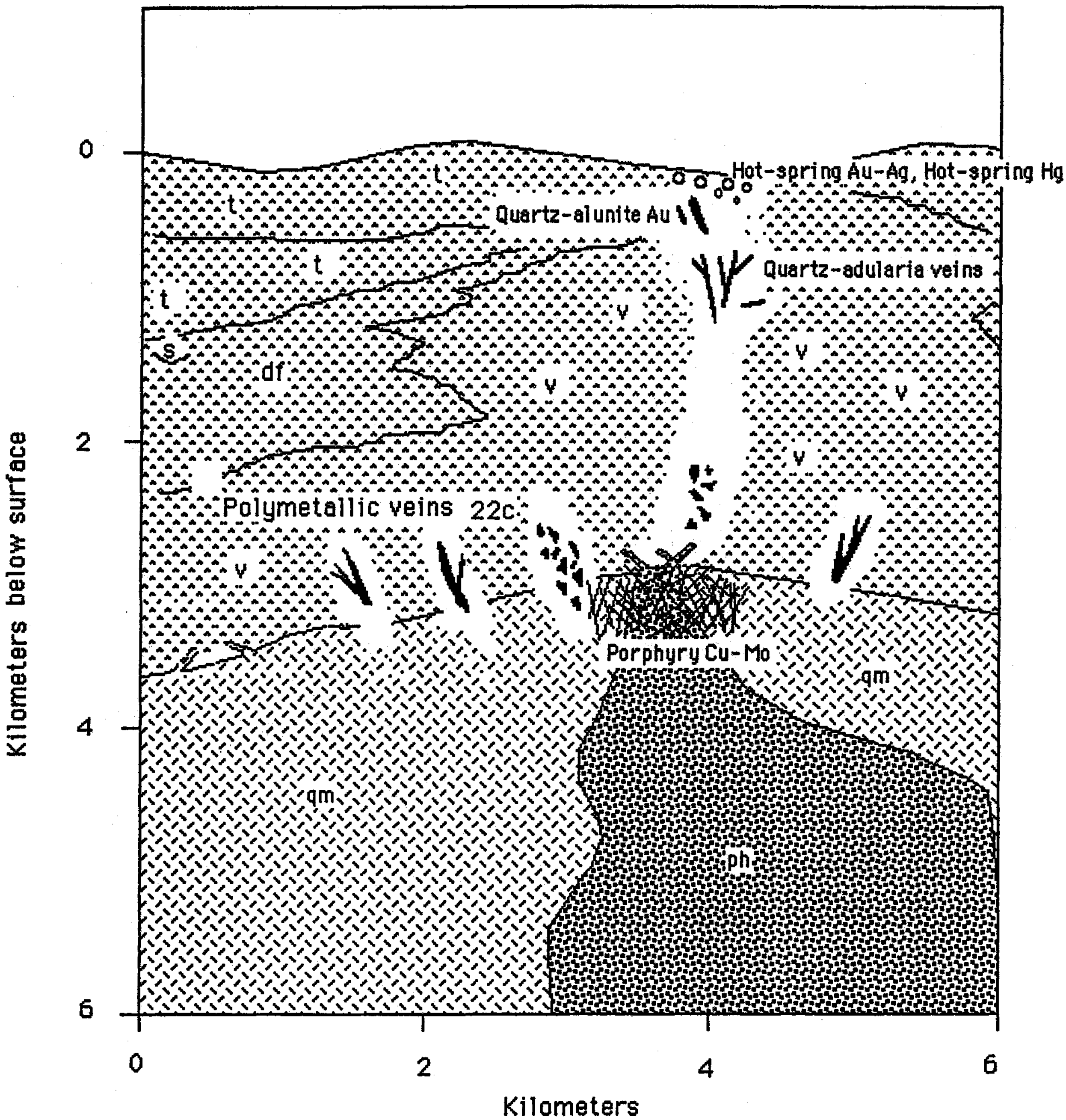

Figure 2. Porphyry-Cu-type intrusion emplaced at deeper crustal levels. qm, quartz monzonite; ph, porphyry; v, volcanic flows; df, debris flows; s, volcanoclastic sediments; t, tuffs.

face the two groups of deposits are likely to occur. Although denudation (erosion) rates show a great deal of local variability, it may be useful to examine how quickly average rates of denudation would expose different levels of a volcano-plutonic complex. Schumm (1963) cites average rates of denudation that varied between 30 and 110 meters per million years (m.y.) depending upon precipitation. Heald and others (1987) report data on the depth to the top of ore and on the vertical extent of mineralization for epithermal precious metal veins. Their data suggest that the bases of epithermal mineralization will lie at a depth of 500–1,600 m in a volcano-plutonic complex. Even a relatively slow rate of denudation (30 m/m.y.) will erode a volcano-plutonic complex to a depth of 1,600 m in 50 m.y.

This preliminary calculation suggests that epithermal precious metal deposits will be exposed and destroyed within about 50 m.y. of their formation, except under special conditions that either result in unusually slow rates of denudation or protect the volcano-plutonic complex from erosion. Table 3 presents ages of mineralization based upon radiometric data for Tertiary epithermal pre-

Table 3. Ages of mineralization of Tertiary epithermal precious metal vein districts (data from Mosier and others, 1985).

Age of mineralization (5 Ma)	Number of districts
0–9.9	10
10–19.9	19
20–29.9	5
30–39.9	1
40 and older	1

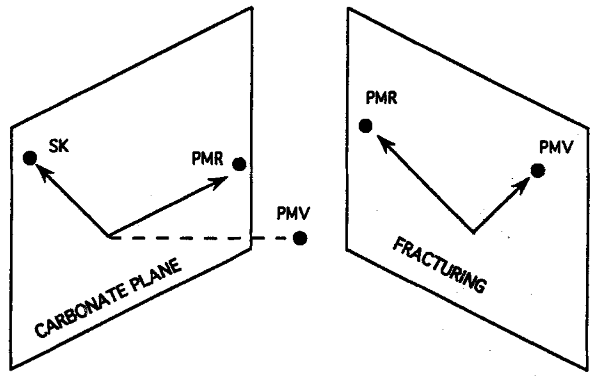

Figure 3. Schematic diagram using vector spaces to show the commonality between skarn (SK), polymetallic replacement (PMR), and polymetallic vein (PMV) deposits.

cious metal vein districts (Mosier, Menzie, and Kleinhampl, 1985). These data support the suggestion that most volcano-plutonic complexes will be eroded to a point below where they contain epithermal precious metal vein deposits in 50 m.y.

Spatial Associations of Mineral Deposits Related to Intrusive Centers

The size of the volcano-plutonic complex and spatial mineral deposit models can provide a basis for estimating the number of porphyry systems present, and information about the level of denudation of the complex can assist in deciding if deposits associated with the extrusive parts of the complex have been preserved. In addition, the assessment must also include estimates of the occurrence probabilities for the number of each type of deposit (veins, skarns, replacement, breccia pipes, and porphyry stockworks bodies) that may have been created by the porphyry systems active during the geological history of the region under study. The number and the type of kin deposits that will occur are determined by the degree to which the conduits for convective flow (faults and fractures) and the types of wall rock that are present interact with the hydrothermal systems. The task before the resource assessor is to judge from the available geologic data whether a porphyry system(s) was active in the area and how the metals carried by this system may have been dispersed through and/or trapped by the wall rock. Certain concepts from linear algebra can be used to assist the resource assessment analyst in the task of estimating occurrence probabilities for the deposits that may occur adjacent to porphyry centers. For this purpose, we advocate a scheme based upon using the framework of an ordered set of occurrence probabilities and/or their equivalent expectations. This scheme uses a vectorial representation, part of which is presented in figures 3 through 8, to visualize the collection of occurrence probabilities (expectations). It is intended to be a guide to assist resource assessors in their work.

Figure 3 shows two planes that represent the existence of through-going fractures and of carbonate rock in the study area. Through-going fractures must have a vertical extent of at least 0.5 km and be open during the period of activity of the geothermal system associated with an intrusive center. The carbonate plane contains the skarn (SK) and polymetallic replacement (PMR) vectors, illustrating the association between the occurrence of these types of deposits and the existence of carbonate or other reactive rock in the study area. The PMR deposits also are in the fracturing plane, illustrating that these deposits are formed when hydrothermal fluids are allowed to "leak off" and encounter carbonate rock in a lower temperature regime than is required to create a skarn deposit. The vector characterizing the occurrence of polymetallic vein (PMV) deposits also lies in this plane.

A degree of freedom is lost with the imposition of the requirement that both carbonate rock and fracturing must be present to create a PMR deposit versus creating either SK or PMV deposits (figure 4). If a hydrothermal system could give rise to no more than one deposit of each type, then the loss of this degree of freedom would imply that within the metallogeny of a porphyry hydrothermal system, PMR deposits ought to occur less frequently than either SK or PMV deposits. Symbolically, we can state that in expectation, the number of polymetallic replacement deposits [*E*(PMR)] that occur in a specific piece of land that is permissive for the occurrence of porphyry-type deposits is less than either the number of skarn [*E*(SK)] or polymetallic vein deposits [*E*(PMV)]:

$$E(\mathrm{PMR}) < E(\mathrm{SK}), \qquad (1a)$$

$$E(\mathrm{PMR}) < E(\mathrm{PMV}). \qquad (1b)$$

Because deposits may be either lumped or split as a result of local geological conditions or conditions of their exploitation, the observed numbers of deposits may vary from this expected form. This results from ambiguities

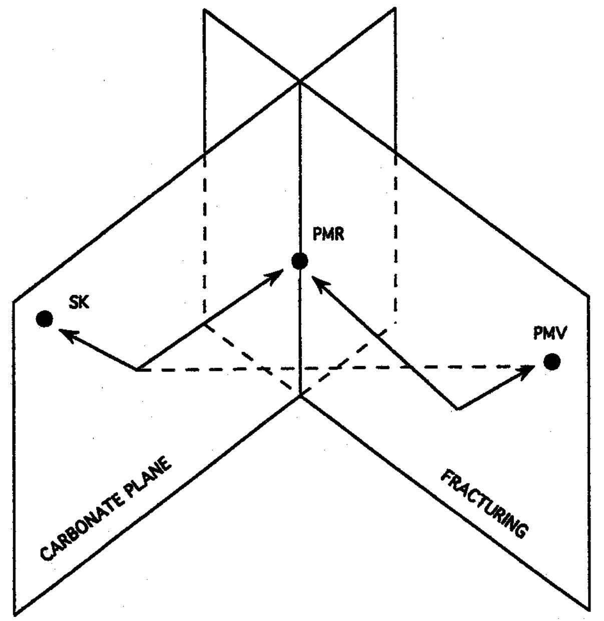

Figure 4. Schematic diagram for relative likelihood of occurrence of PMR, SK, and PMV deposits.

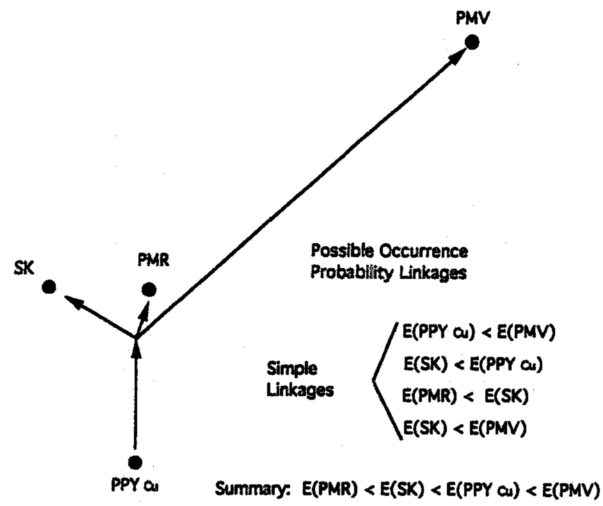

Figure 5. Schematic diagram showing possible linkage between deposit types in the porphyry copper system. Lengths of vectors are proportional to the expected number of deposits.

in defining mineral deposits, and supports the need for operational definitions, such as that given by Bliss and Cox (1986).

If we assume that fractures occur more commonly near metal-bearing porphyry stocks (motivating intrusives) than do carbonate rocks, we can state that PMV's occur more frequently in a permissive area than do SK deposits:

$$E(\text{PMV}) > E(\text{SK}). \quad (2)$$

We can then write the larger inequality conditional upon the permissiveness of the host rocks for the occurrence of each type of mineral deposit, such as the presence of carbonate rocks for skarn and replacement body formation:

$$E(\text{PMV}) > E(\text{SK}) > E(\text{PMR}). \quad (3)$$

Next we can introduce the expectation that the porphyry deposit occurs and represent its relation to its kin deposits (figure 5). In this vectorial representation, the length of the respective vectors represents the magnitude of the expected number of deposits that occur in this porphyry system (see eq. 3). Research must be done to estimate the relative lengths of these vectors.

One possible avenue is to use the ratios of the observed frequencies of the past discovery of the various types of deposits; for example, the ratio of discovery of porphyry deposits [all types—copper (PPY_{Cu}), copper-molybdenum ($PPY_{Cu\text{-}Mo}$), low-fluorine molybdenum ($PPY_{Mo(lf)}$), and Climax molybdenum ($PPY_{Mo(C)}$)] to the discovery of PMR deposits is about 5 to 1 (Cox and Singer, 1986). The ratio of the lengths of the copper porphyry vector (PPY_{Cu}) and the PMR vector are drawn schematically in figure 5 to reflect such a ratio. The lengths of each of the other vectors shown in this figure are schematically displayed in the same manner.

Although conceptually the ratios of the number of discovered deposits of different types should provide an estimate for the vectorial lengths in figure 5, for actual measurement of these lengths, we must know (1) the operational rules used to define what constitutes a deposit, and (2) whether sampling biases are distorting the observed ratios of occurrence of different types of deposits. Operational rules for defining deposits are necessary because nature does not always segregate minerals into clearly recognizable discrete entities and because geologists, mining engineers, and mineral economists do not always record data separately for individual deposits. Several types of sampling biases may affect the apparent ratios of the vector lengths. First, differences in the relative investment attractiveness of different types of deposits will lead to selective representation of these deposits in the sample of identified deposits. Second, regional geological conditions will also influence the vector lengths; for example, the amount of limestone in a region may cause skarn and replacement deposits to be relatively more common in one region than in another, and level of emplacement or erosion may also affect the ratios. Finally, selective misclassification of deposits can result in biased estimates of the relative vector lengths.

The mineral deposits associated with a porphyry-copper-type intrusive center include at least the following deposit models: (1) porphyry copper (Cox, 1986a; Singer and others, 1986), (2) porphyry-copper-skarn-related deposits (Cox, 1986b; Singer, 1986), (3) polymetallic replacement deposits (Morris, 1986; Mosier, Morris, and Singer, 1986), and (4) polymetallic veins (Bliss and Cox, 1986; Cox, 1986c). Copper skarn deposits (Cox and Theodore, 1986; Jones and Menzie, 1986) are not included because they are not related to porphyry systems. The operational rules used to define deposits in the porphyry-copper-skarn-related model imply that no more than one porphyry-copper-skarn-related deposit can occur with a porphyry copper deposit. Further, the definition implies that a porphyry copper deposit is a necessary condition for the existence of a porphyry-copper-skarn-related deposit.

Similarly, the use of districts to construct the polymetallic replacement model implies that it would be very uncommon to have more than one polymetallic replacement deposit (in the sense of the deposit model) associated with a porphyry copper deposit. Further, it is not clear that a porphyry copper deposit is a necessary condition for the existence of a polymetallic replacement deposit. The operational definition of PMV deposits—"workings within 1 km of each other and having a minimum of 100 tonnes of ore" (Bliss and Cox, 1986, p. 126)—implies that more than one PMV deposit can be associated with a porphyry copper deposit. This operational definition allows one to set an upper bound on the number of these deposits that can be associated with porphyry copper models. Because all workings within 1 km of each other are combined to form a deposit, each deposit may be said to occupy an area of at least π km². Empirical data (Guthrie and Moore, 1978; Wilkinson and others, 1982) and theoretical models of the heat flow around porphyry systems (Norton, 1982) suggest that the zone of occurrence of PMV deposits has a radius of 3 to 7 km. If we compare the area of the zone of occurrence of PMV deposits to the minimum area that each polymetallic vein occupies, we may calculate an upper bound on the number of polymetallic veins that may be associated with a porphyry copper deposit. Such a calculation suggests that the upper bound lies in the range of 9 to 49 deposits. The empirical data suggest that the lower part of the range is probably a reasonable upper bound.

Because polymetallic veins are not particularly attractive exploration targets and because deposits of that type were exploited in an earlier period, we may assume that such deposits are relatively more common than would be indicated by comparing the number of deposits in the polymetallic vein model to the number of deposits in the porphyry copper deposits. Also, local conditions will affect the relative abundance of deposits of each type in the porphyry copper system. For example, in Arizona it appears that there is about one porphyry-copper-skarn-related deposit for every seven porphyry copper deposits; it is not clear that this ratio would hold for a different porphyry belt. Therefore, although ratios of numbers of deposits in different deposit models and upper bounds calculated on deposit and system sizes are useful first-order approximations of vector lengths, more precise measures of these lengths will require thorough modeling of the deposits of several porphyry belts.

In summary, as a first approximation, it appears the occurrence probabilities in the copper porphyry system are ordinally linked in the schematic diagram shown in figure 5 as follows:

$$E(\mathrm{PMR}) < E(\mathrm{SK}) < E(\mathrm{PPY_{Cu}}) < E(\mathrm{PMV}). \qquad (4)$$

This linkage implies that under normal conditions of permissiveness in the metallogeny of porphyry systems, it is expected that PMR deposits are the least likely type of deposit to occur, whereas PMV deposits are the most likely type of deposit to occur.

Resource assessors must be aware that the permissiveness for the occurrence of one type of deposit is normally linked to the permissiveness of other types of deposits within the same metallogenic system [for example, the porphyry system(s)]. The assessor should not think of land areas, unless otherwise specified, as being permissive for the occurrence of single deposit types. Rather, assessments ought to be performed for the collection of deposit types that can be produced by a mineralizing system as it interacts with the wall rock. The assessor must also be aware that many questions about the genesis of deposits such as PMV's are not yet completely understood. Clearly some of the deposits used to construct the grade and tonnage model of PMV's (Bliss and Cox, 1986) are not related to porphyry copper systems. This model will likely be subdivided to include models of veins associated with porphyry systems and silver-lead-zinc veins in clastic metasedimentary terranes (Beaudoin and Sangster, 1992).

In this regard, the resource assessor may profit from gaining a working knowledge about the various points of view that prevail and change from time to time on the origin and classification of mineral deposits. The pendulum has swung back and forth from the orthomagmatist view that magma is the sole source of metals and transport fluids to the opposite position that metals and transport fluids are derived from the wall rock. In the nonmagmatic view, intrusive igneous rocks serve only as heat sources to drive convective cells that charge meteoric waters with ionic complexes that extract and carry the

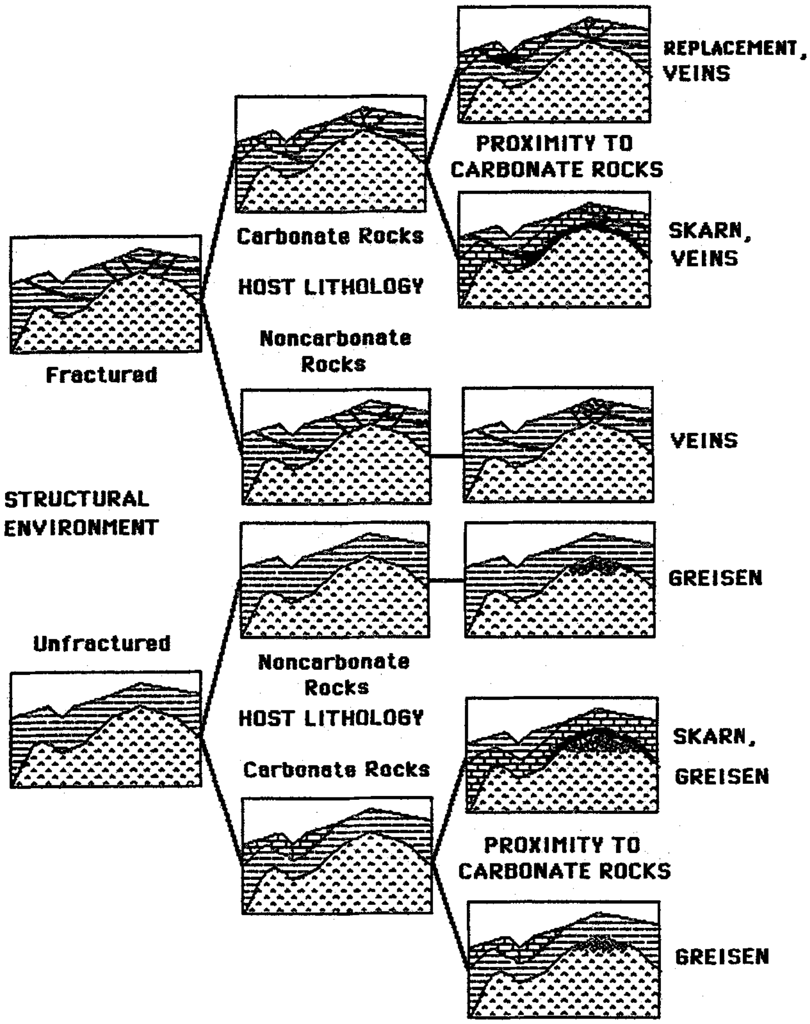

Figure 6. Decision tree showing diagrammatic cross section of possible relations of granite plutons, structural features, wall rock, and permissiveness for lode tin deposits.

metals to sites of deposition. The resource assessor has to use these ideas to interpret mineral deposit and occurrence data and to induce the types of mineral deposits that remain to be discovered in an area. As a case in point, what should the resource assessor conclude from the existence of several small PMV's in the study area? Are these veins part of a yet-to-be-discovered porphyry-skarn-replacement-vein metallogenic system or are they the product of a hydrothermal convective cell that caused the circulation of meteoric water through a stratigraphic section (source of the metals) containing an evaporate bed that provided a source of chloride and/or sulfate to the transport fluid?

Researchers in the field of mineral resource assessment are trying to identify ideas and, hopefully, rules to interpret the wide variety of seemingly disparate information that exists on the characteristics of the mineral deposits and occurrences. It is easy to be confused by the varying characteristics that mineral deposits may exhibit depending upon the configurations of wall rock and structure and their interaction with the material contained in a convective hydrothermal cell. The varying effects of this interaction gave rise to the idea that no two mineral deposits are really the same. The resource analyst must turn the thoughts of economic geologists about the origins of mineral deposits into models and rules useful for assessing the types and possible sizes of undiscovered mineral deposits.

These models and rules must be flexible so the resource assessor can consider the idea that the wall rocks, which host mineral deposits in various structures, have phenomenologically confused the appearance of certain mineral deposit types. The resource assessor has to deal with uncertainty inherent in conflicting hypotheses about the origin of mineral deposits, because he or she is charged with assessing the undiscovered mineral resources in a certain region. The resource assessor does not take the existence of a mineral deposit as a given and try to determine its origin, that is, work from "inside" a deposit "outward" to its origin. Instead, the resource assessor has

Table 4. Estimated number of deposits at different coincidence levels.

Deposit type	Chance that at least the indicated number of deposits are present		
	90%	50%	10%
Skarn	5	9	15
Replacement	1	2	4
Greisen	2	3	5
Vein	1	2	4

to start from "outside" of the deposits that may remain to be discovered in a region and work "inward" toward a solution to the assessment problem.

A model similar to that developed here for volcano-plutonic complexes that host porphyry copper systems was used by Reed and others (1989) in their assessment of the undiscovered lode tin resources of the Seward Peninsula, Alaska. The main operational element used in this assessment was a decision tree (figure 6) representing possible environments of emplacement of intrusive centers. Using the decision tree produced consistent results in the assessment (table 4). The quality of consistency is demonstrated by the fact that the expected number of skarn deposits is greater at each probability level than the expected number of replacement deposits; the same is true for the expected number of greisen versus vein deposits.

Toward a General Model of Porphyry Systems

Figure 7 presents a general model for assessment of porphyry systems. The base plane of this figure contains three vectors. The degree to which these vectors are separated (ϕ, θ, $\theta - \phi$, and so forth) characterizes the uniqueness of the processes that generate the porphyry deposits. The solid part of a single vector separated by a dashed portion represents differences in the material inputs to a generating process. Notice that the porphyry copper system (PPY_{Cu}) and the porphyry copper-molybdenum system are generated by the same process with different material inputs (such as the type of protolith melted). Stated another way, these two types of deposits have a common heritage in their generating process; the differences used to classify them into separate groups reflect the continuum in the chemistry of the rocks that can be melted in a subduction zone.

Also depicted in figure 7 is the idea that the low-fluorine molybdenum porphyry deposits ($PPY_{Mo(lf)}$) are generated by a somewhat different subduction process (represented by the angle ϕ) and different material inputs than the copper porphyry deposits (PPY_{Cu}). The vector characterizing the Climax-type molybdenum porphyry

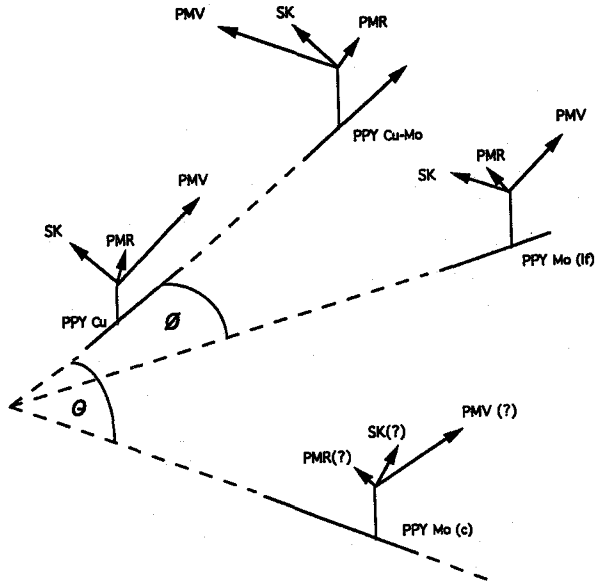

Figure 7. Schematic diagram showing possible occurrence probability linkages for the deposit types associated with the porphyry systems. The lengths of the vectors are proportional to the number of deposits expected to occur.

deposits is disposed at the much larger angle θ, representing the idea that these deposits are formed far from continental margins, after subduction has stopped, in a unique anorogenic environment (Bookstrom, 1981).

An additional idea is depicted in figure 7. There are no known Climax-type molybdenum deposits ($PPY_{Mo(C)}$) with associated PMV, SK, and PMR deposits of sufficient size to be "on" any of the existing grade and tonnage models representing these kin deposits. However, there is no conclusive reason why there should not be associated kin deposits with Climax-type porphyry deposits. Consequently, a swarm of the kin deposits is placed at the apex of this $PPY_{Mo(C)}$ vector in figure 7, alerting the assessment analyst to the possibility that such an association may exist and ought to be considered in the assessment of land areas permissive for the occurrence of this type of porphyry deposit. Question marks are placed at the end of this swarm of vectors representing the tenuous nature of this association.

The resource analyst must be aware that once permissiveness is established for the occurrence of a given mineral deposit and a nontrivial probability of occurrence estimated, additional statements may be implied for other types of deposits. This implication can be positive, as it is for the occurrence of porphyry copper deposits given that an area has been assessed as permissive for the occurrence of, say, PMV and/or porphyry-related SK deposits. The implication may be negative if two deposit types are characterized by genetic processes that are broadly mutually exclusive. If it is plausible that PMV,

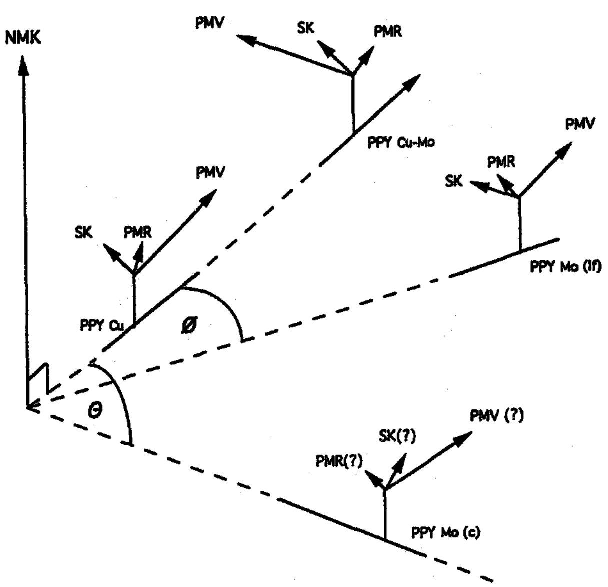

Figure 8. Schematic diagram showing the nonlinkage of the nonmagmatic kin-type deposits to the porphyry deposit systems.

SK, and PMR deposits can be formed by a convective hydrothermal cell that acquires all its transport constituents and metals from the wall rock, that is, there is no contribution from a magma other than enough heat to drive fluid convection, then a nontrivial probability of occurrence of these kin deposits does not imply a linkage between their probabilities of occurrence and the probability of occurrence of a porphyry deposit. In figure 8, the vector NMK (nonmagmatic kin) depicting this situation is disposed at a right angle (independent) to the base plane that contains the four porphyry systems.

Assessment Within a Mining District Versus Yet-To-Be-Discovered Districts

One of the most difficult tasks that the resource assessor faces is the determination of a nontrivial occurrence probability for a yet-to-be-discovered mineralized system. Here a mineralized system is defined as the resulting totality of the effect of a hydrothermal system upon the wall rocks that it has invaded, that is, the collection of all the different types of mineral deposits that can occur as a result of the interaction of a convective hydrothermal system with wall rock. The redistribution of deposits by weathering (placers) and secondary enrichment (for example, chalcocite blankets associated with some porphyry copper deposits) is included as part of this collection of deposits.

The most common argument for determining that a nontrivial probability exists for the occurrence of an undiscovered mineralized system is that only the very top of a system is exposed. This may be a small polymetallic vein or patch of alteration for a porphyry system, or perhaps extreme distal portions of a sedimentary exhalative zinc-lead district exist, such as a bed of barite or hematite (Large, 1980). Another argument used in areas under alluvial cover adjacent to an exposed mineralized system is that a hidden (down faulted) system, or part of a system, exists in probability under the cover. A yet-to-be-discovered mineralized system can also be inferred to exist in probability from the existence of ore-hosting structures, the composition of wall rock, and intrusives (heat sources) or large and deeply connected faults.

It is not uncommon for the assessor to be faced with the task of "filling out" an assessment within known mineralized systems and to assess the probability that yet-to-be-discovered parts of systems occur in the study area. In both cases, the diagrams shown in figures 3–8 offer a useful assessment guide.

When the geological data on the study area are sufficient to conclude that only a trivial probability exists that a new mining district remains to be discovered, the linkages among the probabilities of occurrence can be used to "fill out" a mineral resource assessment. If, for example, permissiveness has been established for porphyry copper deposits and skarn deposits, the resource assessor should include a nontrivial probability that a polymetallic vein and perhaps even polymetallic replacement deposits exist, unless it can be demonstrated that such deposit types cannot occur. Resource assessors ought to examine the possibilities that all the kin deposits associated with a particular metallogenic system occur in the study area and then eliminate the possibilities of occurrence with the available data. The danger exists that assessors may be too restrictive regarding the occurrence of kin deposits because no deposit of this type has been discovered. In the same regard, when a nontrivial probability for the occurrence of a new mining district is estimated, the assessor ought to use the linkages between occurrence probabilities to generate a complete assessment for the yet-to-be-discovered district, including an estimate for all the kin deposits in the metallogeny.

Summary

Quantitative mineral resource assessments are estimates of the quality and quantity of undiscovered mineral wealth in a region. They are by nature region specific. That is, as a real estate assessor must estimate the value of the surface of a piece of land as well as the buildings that sit upon it, a mineral resource assessor must estimate the value of the yet-to-be-discovered mineral resources hidden under its surface. In the past these evaluations were performed to assess the vulnerability of a country to supply disruptions of certain types of mineral raw materials.

Today mineral resource assessments are more often performed to provide a basis for estimating the opportunity cost of the decisions to not use land area for the production of mineral wealth and instead to use the land as wilderness areas and parks.

The technical elements that compose the body of the field of mineral resource assessment are drawn from a disparate group of academic disciplines, but the core of the interdisciplinary field of mineral resource assessment is a group of descriptive and statistical models that summarize mineral deposits as collections of physical entities having common characteristics. The descriptive models are tied to geological concepts and form the basis for assessing whether individual deposits or groups of deposits occur in probability in the study area. The statistical models—grade and tonnage models—summarize the types and volumes of metals that occur with each class of mineral deposit. The total value of all the undiscovered mineral wealth by type of metal occurring in an area is calculated using a computer simulation model.

In this study we develop some metrics for estimating the probabilities of occurrence of various types of mineral deposits that are associated with magmatic arcs and resulting volcano-plutonic complexes. If the tectonic processes that drive arc development are regular, we may expect that the sizes of the resulting volcano-plutonic complexes and the number of intrusive centers within the complexes will also exhibit regularities. Preliminary data suggest that probabilities of occurrence of porphyry copper deposits within the intrusive parts of volcano-plutonic complexes must lie between .000x and .00x deposits per square kilometer. Because different types of deposits are emplaced at different levels in volcano-plutonic complexes, the level to which a complex has been eroded will affect the types of deposits that may occur in an area. Normal denudation rates will remove deposits associated with the volcanic parts of these complexes within 50 m.y.

Finally, this study examines how occurrence probabilities for the various types of mineral deposits related to an intrusive center are linked according to a set of probabilistic inequalities (a metric). The characteristics of this metric (the types of "kin" deposits and the probability that they occur) within a porphyry system, as with most other magmatic related systems, are determined in large part by the type of rocks (wall rocks) that the hydrothermal system comes into contact with. The assertion is made that under average geologic conditions, porphyry systems will generate more polymetallic veins than porphyry deposits, more porphyry deposits than skarns, and more skarn deposits than polymetallic replacement deposits.

The resource assessor must start from the position that all the kin deposits might occur in the study area given that a member of the family occurs, and then proceed by a process of elimination, rather than assessment, for a single deposit type. This approach should be taken whether the task before the assessor is to "fill out" the assessment of an area in which there is a trivial probability that a new mining district remains to be discovered or to estimate the probabilities that yet-to-be-discovered districts with all the kin deposits remain.

In addition to such positive linkages, there may be negative linkages between some occurrence probabilities. This situation would typify the linkage between deposit types that are mutually exclusive. Also, the kin deposits that compose certain metallogenic systems may be characterized as facies equivalents.

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