

## QUANTIFYING MINERAL-DEPOSIT MODELS FOR RESOURCE ASSESSMENT

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### ABSTRACT

Mineral-deposit models are an integral component of any mineral-resource assessment methodology. Pushing forward the frontiers of the state-of-the-art in deposit models is important in helping to meet the need for mineral-resource assessments to be carried out more efficiently and cost effectively, and become useful as predictive tools in quantitatively forecasting favorable sites for deposit occurrence. Advances in the understandings of plate-tectonic environments and the coupling of thermal, mechanical, and hydraulic phenomena in hydrothermal systems provide avenues for exploring aspects of mineral-deposit models that might improve them. These understandings underscore the importance of far- and near-field stresses on fluid flow in ore-forming systems and the potential of paleostress analysis to be integrated into models.

Hierarchical schemas are most frequently used to classify mineral deposits for assessments because they provide a mechanism for subdividing regions being assessed into permissive terranes. Three general categories of typical hierarchical schemes are both suitable and potentially amenable to applying coupled physical phenomena in the quantification of models—regional terranes, the landscapes within which deposits occur, and the attributes that describe the deposits *per se*. Using epizonal deposits in a continental-arc environment as an example, this paper explores some of the possibilities to quantify mineral-deposit models.

### 1. INTRODUCTION

Whether one's goal is exploration, economic development, or land-use planning, estimating where and the probable quantities of undiscovered mineral deposits<sup>1</sup> are important, but uncertain, undertakings. At the heart of any methodology used to estimate undiscovered deposits are mineral-deposit models. They are the basis for assuring consistency throughout all steps of an estimation process (SINGER 1993a). Minimizing uncertainties in deposit models decreases the overall uncertainty in their application.

Increasing labor and technology costs worldwide and the need to balance environmental versus resource-exploitation demands make it imperative that the analysis of geological information and its interpretation as to the undiscovered mineral deposits be done as efficiently and precisely as possible. Greater precision is accomplished by decreasing the uncertainty and improving the predictive capability from models. This may be accomplished through increased understanding about the localization of mineralizing systems, the formation of ore bodies within mineralizing systems, and the quantification of descriptive deposit information. This is the state-of-the-art in mineral-deposit modeling.

It is our purpose in this paper to propose a frame of thinking about hydrothermal mineral deposits that we believe will greatly improve the utility of models of them. Because the specific content of models depends to a certain extent on their application (HENLEY and BERGER 1993), our goal herein is on modeling for economic devel-

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<sup>1</sup> We use the term "mineral deposit" in the context of Cox et al. (1986) wherein a mineral deposit is a mineral occurrence of sufficient size and grade that it might, under the most favorable circumstances, be considered to have economic potential.

opment and land-use planning purposes<sup>2</sup>. The discussion focuses on three aspects that we believe will improve the predictive capabilities of these mineral-deposit models: (1) lithotectonic terranes, (2) dynamic landscapes and evolving mineralizing systems, and (3) the quantification of model attributes and linkages between commonly associated mineral-deposit types. The epizonal<sup>3</sup> magmatic-hydrothermal environment is used for illustrative purposes, but the concepts discussed are based on first principles and are, therefore, applicable to other ore-forming environments.

## 2. A FRAME OF THINKING ABOUT MINERAL DEPOSITS

Hydrothermal mineral deposits are a natural part of petrogenetic processes. Studies of volcanoes, hot dry-rock geothermal areas, and nuclear waste disposal problems have shown that, in fluid-flow systems, thermal, mechanical, and hydraulic phenomena are interdependent (cf. NOORISHAD et al. 1984, INGEBRITSEN and SANFORD 1998). Therefore, mineralizing systems must be modeled as the totality of the complex coupled phenomena that form them, not by only one or two of the phenomena.

Although oversimplified for ore-forming systems, the coupling of forces and flows may be expressed as

$$q = -K\nabla H - K_T\nabla T - K_C\nabla C_S,$$

where the flow,  $q$ , is a function of the hydraulic conductivity ( $K$ ), the hydraulic gradient ( $\nabla H$ ), thermal conductivity ( $K_T$ ), thermal gradient ( $\nabla T$ ), chemical conductivity ( $K_C$ ), and chemical concentration gradient ( $\nabla C_S$ ). The coupled heat and chemical transport aspects of the flow equation have been the focus of ore-genesis research for several decades. However, the interdependence of flow and deformation in ore-forming systems is less well-studied. The importance of deformation to fluid flow is manifested in part through the equivalent hydraulic conductivity which, in a rock with parallel planar fractures, is

$$K = \frac{\rho_w g N b^3}{12 \mu [1 + C(x)^n]},$$

where  $\rho_w$  is the fluid density,  $g$  the acceleration of gravity,  $\mu$  the dynamic viscosity,  $b$  the fracture aperture,  $N$  the number of fractures per unit distance across the planar rock face, and  $C(x)$  the set of variables that describe fracture roughness (DOMENICO and SCHWARTZ 1998). The relation of aperture to hydraulic head gradient is cubic because, for a given gradient, flow through a fracture is proportional to the cube of the fracture aperture. Disregarding fracture roughness, the permeability,  $k_x$ , is

$$\frac{N b^3}{12}.$$

Deformation also triggers heat and chemical transport processes. Coseismic dilatation and decompression of a fracture network results in heat transfer from the host rock between the fractures to the fluid in the fractures and an increase in the vapor fraction in the fracture network (HENLEY and HUGHES in press). The separation of the vapor fraction potentially increases the solute concentrations in the remaining liquid fraction. The vapor fraction increases as fracture density and interconnectivity increase. In addition, the proximity to the fracture network at which the vapor fraction increases diminishes as the fracture spacing decreases. Thus, mineral deposition is dependent on deformation and fracture-network size and geometry.

Within any flow system—magmatic, hydrothermal, or groundwater—fluid flow is perpendicular to the least principal stress ( $\sigma_3$ ) and parallel to the maximum principal stress ( $\sigma_1$ ) (cf. NAKAMURA 1977, ZOBACK and ZOBACK 1980, TSUNAKAWA 1983). Laboratory and field experiments confirm the relation between principal stresses and fluid flow (HAIMSON 1974, BARTON et al. 1995). This relation is of considerable importance in reconstructing the paleostress conditions affecting magmatic and hydrothermal activity in mineralized areas.

<sup>2</sup> Although we do not specifically mention models for minerals exploration, the quantitative models we propose would be applicable to exploration strategies that attempt to estimate the number of targets within some terrane, rank target areas, and estimate the uncertainty of occurrence at a specific site.

<sup>3</sup> We use the term "epizonal" in the context of all mineral deposits generally formed at  $\leq 4$  km depth in the earth's crust.

### 3. IMPROVING THE PREDICTIVE CAPABILITIES OF MODELS

#### 3.1. Lithotectonic terranes

The plate-tectonic model of the earth provides a consistent set of describable dynamic processes and landscapes, landscapes that evolve, are modified, and come and go in time and space. This consistency of process leads to there being a correlation between mineral-deposit types and geologic terranes. Thus, lithologic/tectonic landscapes derived from plate motions make a logical framework around which to categorize each mineral-deposit type. Table 1 summarizes selected epizonal magmatic-hydrothermal deposit types in the context of plate tectonic lithotectonic terranes associated with convergent plate margins.

**Classification of selected epizonal magmatic-hydrothermal mineral deposits.**  
Epizonal deposits herein are defined as those forming at  $\leq 4$ -km depth

Table 1

#### **I. Deposits produced along convergent tectonic-plate margins**

##### **A. Magmatic arcs above subduction zones**

1. Porphyry type
  - a. Porphyry Cu subtype
  - b. Porphyry Cu-Au subtype
  - c. Porphyry Cu-Mo subtype
2. Skarn type
  - a. Cu, Cu-Au subtype
  - b. Fe subtype
3. Polymetallic type
  - a. Replacements
  - b. Veins
4. Epithermal-style deposits
  - a. Quartz-adularia-illite type deposits
    - (1) Sado subtype
    - (2) Comstock subtype
    - (3) Creede subtype
  - b. Quartz-alunite-kaolinite±pyrophyllite type deposits
    - (1) Au, Au-Cu, Cu subtypes
    - (2) Polymetallic subtype

##### **B. Back-arc environments**

1. Back-arc basin spreading centers
2. Continental back-arc regions
  - a. Epithermal-style deposits
    - (1) Quartz-adularia-illite type deposits
      - i. Sado subtype
      - ii. Comstock subtype
      - iii. Creede subtype
    - (2) Quartz-alunite-kaolinite±pyrophyllite type deposits
      - i. Au, Au-Cu, Cu subtypes
      - ii. Polymetallic subtype
  - b. Porphyry type
    - (1) Porphyry Cu-Mo, Cu-Au subtypes
    - (2) Granodiorite-related porphyry Mo subtype
  - c. Skarn type
    - (1) Polymetallic, Au±Cu subtypes
    - (2) Fe subtype
    - (3) W subtype
    - (4) Sn±W subtype
  - d. Polymetallic type
    - (1) Replacement subtype
    - (2) Vein subtype

##### **C. Tectonic-plate accretion: suture-related shear zones**

1. Hg veins and replacements
2. Sb veins and replacements

##### **D. Continental-margin transform environments**

1. Porphyry type
  - a. Climax-style porphyry molybdenum deposits
  - b. W subtype
  - c. Be subtype
2. Skarn type
  - a. Sn±W subtype
  - b. W subtype
3. Sn-replacement type ± veins

### 3.1.1. Current USGS approach to regional classification

Since the early 1980s in US Geological Survey (USGS) mineral-resource assessments, the most common way to classify mineral deposits in a regional geologic context has been lithologic associations. For example, COX and SINGER (1986) subdivide epizonal magmatic-hydrothermal deposit models into lithologic groupings as shown for some deposit types in Table 2. Within a model, such as Comstock epithermal vein deposits (model 25c; MOSIER et al. 1986), the lithologic setting is simply calc-alkaline or bimodal volcanism, and the regional tectonic setting is “through-going fracture systems” or “major normal faults”. This lithologic approach to classification is qualitatively useful, but does not provide information on the frequency of occurrence of any of the stated attributes. In addition, this approach does not provide an explanation as to why some geologic terranes ostensibly permissive for the occurrence of undiscovered deposits of a specific type have, in fact, few or none. In section 3.1.2 we consider a plate-tectonic environment—magmatic arcs in subduction zone settings—as an example, with emphasis on those aspects which portend amenability to forming distinct populations.

**Selected example of mineral-deposit models classification used by COX and SINGER (1986)**

*Table 2*

**1. Deposits related to felsic porphyrophanitic intrusions**

- Model 16 Climax Mo deposits
- Model 17 Porphyry Cu deposits
- Model 18a Porphyry Cu, skarn-related deposits
- Model 20c Porphyry Cu-Au deposits
- Model 21a Porphyry Cu-Mo deposits
- Model 22b Au-Ag-Te vein deposits

**2. Deposits related to subaerial felsic to mafic extrusive rocks**

- Model 25a Hot-spring Au-Ag deposits
- Model 25b Creede epithermal vein deposits
- Model 25c Comstock epithermal vein deposits
- Model 25d Sado epithermal vein deposits
- Model 25e Epithermal quartz-alunite Au deposits

### 3.1.2. Example of lithotectonic terrane: Magmatic arcs

Subduction zones are regions along convergent tectonic-plate boundaries where relatively cold and dense lithospheric plates sink into the earth beneath an opposing overriding plate (TATSUMI and EGGINS 1995). These zones are commonly divided into subregions: forearc, volcanic arc, and back arc. The magmatism and surficial volcanism typically occur in the overriding plate in a linear belt (“volcanic front”) parallel to the convergent plate margin, and quite consistently are situated about 100-200 km above the subducting slab. The most common occurrence of epizonal magmatic-hydrothermal mineral deposits is in magmatic arc environments.

Subduction induces significant chemical change in the earth’s lithosphere, and magma formation is one consequence of the geochemical processes. Studies of subduction-related igneous rocks have shown them to be chemically distinct and many studies show there to be some systematic variations in igneous rock chemistry across arc terranes. Because of the focus of economic geology research on heat and chemical transport phenomena, the chemistry of magmas within subduction zones has been studied in an effort to find relations that could be used to determine if there are “productive” and “nonproductive” magmas. However, thus far no unique relations between deposit type and magma chemistry have been identified. Quantifying the chemistry of rocks associated with mineral deposits in magmatic arcs is probably not worthwhile.

Although subduction zones are dynamic, there are systematics across them that may produce metrics useful in mineral-deposit classification at the terrane scale and the prediction of where mineralizing systems are likely to occur in magmatic-arc terranes. There are topographic systematics (outer rise, trench, shelf, island arc), the topography and free air gravity are positively correlated, and the width of the positive gravity anomaly over the magmatic arcs is about the same width as the trenches (HAYES and EWING 1970). MELOSH and RAEFSKY (1980) suggest that the latter correlation implies a single, dynamical process, and showed through numerical modeling that the forces involved are due to viscous stresses<sup>4</sup> generated by the bending of the lithosphere as it is being sub-

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<sup>4</sup> Viscosity is the property of a fluid or semifluid to maintain a shear stress as a function of velocity and pressure.

ducted and to a lesser extent the elasticity of the lithosphere. The stresses are propagated upward and affect tectonic phenomena and fluid flow in the overriding plate.

Another measurable attribute of arcs is the distribution and numbers of volcanoes. Distribution and numbers are affected by the thermal structure of the mantle wedge. In some arcs (e.g., Aleutian, Kamchatka, Kurile, NE Japan, Indonesia, and Scotia) there are two volcanic chains, while others have only a single chain (e.g., Mariana, Tonga-Kermadec, Central America, and Lesser Antilles) (TATSUMI and EGGINS 1995). MARSH (1979) found that the width of a volcanic arc is inversely proportional to the angle of subduction, with wider arcs forming above more shallowly dipping subducting slabs. The volume of erupted volcanic material is greatest at the volcanic front and decreases toward the back-arc side; large-volume calderas are more common along the plate boundary side of the arc. In the Northeast Japan, New Zealand, and Kurile arcs, there is a higher extent of differentiation on the plate-boundary side of the arcs than on the back arc side. Taken together with the greater volume of erupted volcanic material, these facts require that considerably more magma is produced on the plate-boundary sides of arcs, which TATSUMI and EGGINS (1995) speculate is a reflection of a greater amount of volatile flux. Also, the flux of volatiles has important implications for mineral deposit formation as discussed below. The number and density of volcanoes is positively correlated with the rate of subduction (SHIMOZURU and KUBO 1983). A greater rate of subduction increases the flux of dehydration fluids from the greater volume of material being subducted, which in turn leads to higher rates of melt production in the overlying mantle wedge (TATSUMI and EGGINS 1995).

In the Taupo Volcanic Zone, New Zealand, there are a large number of high-enthalpy geothermal systems (Fig. 1). The high-gas, metalliferous systems are considered to be most analogous to ore-bearing epithermal systems. But, these metalliferous systems are not randomly distributed with respect to the tectonic elements in the

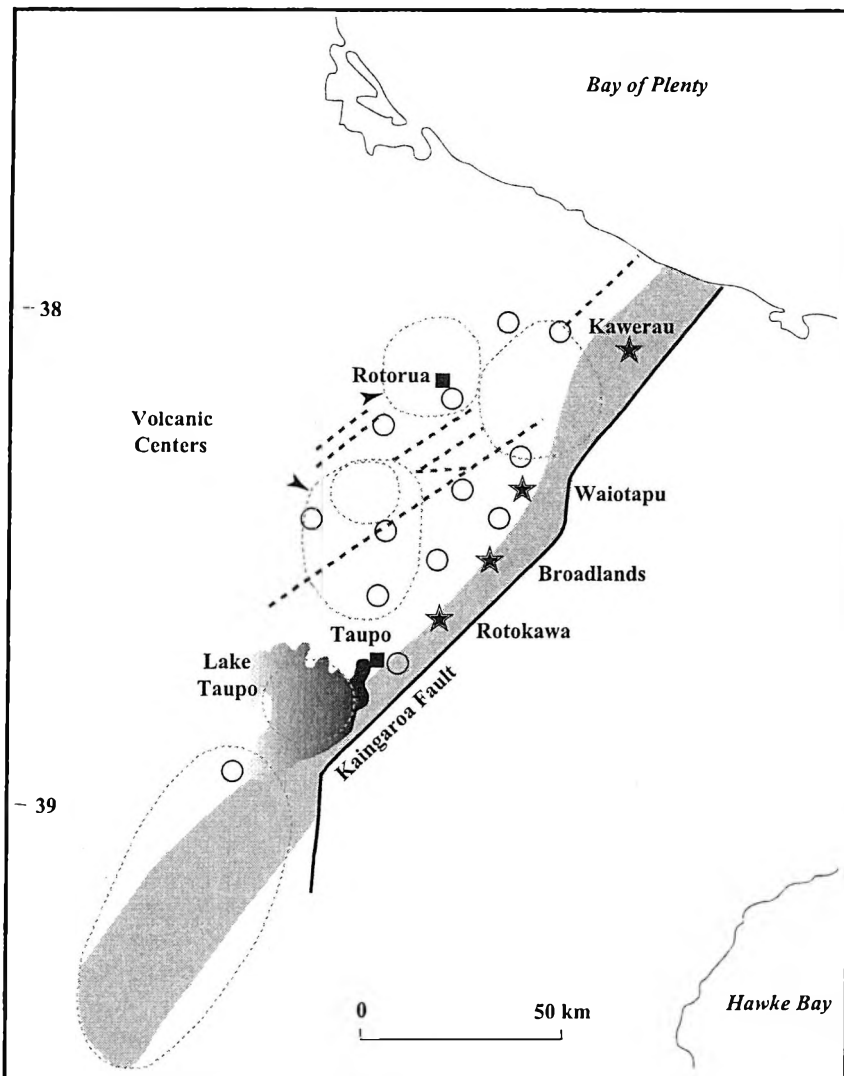


Fig. 1: The spatial relation of high-enthalpy, high-gas metalliferous geothermal systems (M) in the Taupo Volcanic Zone and the crustal-scale Kaingaroa fault and the andesitic continental-arc volcanism (shaded area). High-enthalpy, low-gas and low metal geothermal systems are shown by open circles (after BERGER and HENLEY, 1989)

Taupo zone. They all occur along a single tectonic line—the “Andesite Line”—at the front of the magmatic arc. High-enthalpy geothermal systems not along the Andesite Line are low-gas and low-metal. Dissolved gases, especially H<sub>2</sub>S and CO<sub>2</sub>, are important in ore formation. The implication is that deep-seated, basement penetrating fracture zones are necessary to the formation of metalliferous geothermal systems in active magmatic arcs.

*Implications for mineral-resource assessments of magmatic-arc terranes.* The consistency of igneous-rock chemistry in different plate-tectonic settings implies that paleo-arc terranes can be delineated. This is an important first step in drawing boundaries around terranes permissive for the occurrence of undiscovered deposits of a specific type that are known to be associated with these arc terranes. In addition, the metallogenesis of known mineral deposits within a permissive terrane provides information on the general composition and possible geochemical evolution of regions within the lithosphere where magmas are produced and on the extent of metasomatism due to devolatilization above the subducting slab. For example, within the State of Nevada, common Jurassic epizonal deposits are porphyry copper, polymetallic vein, and iron skarn types. By the Cretaceous, metasomatism of the lithosphere had been sufficient for iron skarn to diminish in abundance and tungsten skarn deposits to become common.

The links between the physical architectures of the magmatic arc and back-arc regions, the volume and localization of magmatism, localization of high-enthalpy and metalliferous geothermal activity, and the far-field stresses imply that systematics may occur in groups of terranes with characteristics having a high likelihood of predictability. Careful analysis may elucidate those aspects of modern arcs that can provide reliable population statistics. In addition to geologic variables, there are also possibilities in geochemical indicators such as across-arc variations in <sup>87</sup>Sr/<sup>86</sup>Sr.

Thus, the paleogeography of arc terranes, their structural geology, and the occurrence of crustal-scale basement fracture zones may be used to further delimit areas within permissive tracts for which the undiscovered deposit potential is more favorable.

### 3.2. Dynamic deposit landscapes

In most mineral-deposit models, the geology of deposits is more commonly portrayed in cross-section than in plan view (cf. KIRKHAM et al. 1993). Analogs of the sedimentary-rock facies models are seldom applied to igneous-rock related mineral deposits, and the integration of tectonics and structure into evolving landscapes for models is infrequently found in the literature. However, modeled paleogeographic landscapes including indicators of stress-related dynamics have the potential to significantly improve our ability to predict where and when mineral deposits are likely to occur in any given terrane.

The analysis of the geologic settings of epizonal deposits in the western United States suggests that the settings may be divided into two groups, compressional and extensional. For deposits occurring in compressional environments, epizonal deposits appear to be preferentially localized in stepovers—extensional or contractional—within lateral fault systems. In extensional regimes, higher grade ores are related to transfer structures transverse to the direction of extension or in short length-scale extensional faults between two closely spaced transfer faults. Below, we illustrate what a time-space landscape/dynamics model might look like for a terrane with continental-arc volcanism transitioning over time from an oblique-slip plate-margin setting to a near-field hyperextending setting during volcanism-related hydrothermal activity.

#### 3.2.1. A hypothetical landscape/dynamics model

The intrusion of large volumes of magma into the shallow crust in arc terranes results in uplift and extension. Nevertheless, strike-slip faults parallel the trend of the magmatic arc as a consequence of oblique plate convergence and/or buoyancy contrasts between converging plates (WOODCOCK and SCHUBERT 1994). In such “mixed” tectonic settings, volcanism is frequently localized at releasing bends along strike-slip faults and in transfer zones in extending regimes (GLAZNER et al. 1994).

Most geologic environments have complex histories. Capturing this complexity in generalized models is difficult. Focus must be on the environment existing at the time a mineral deposit of interest was permissive to form. Crustal-scale faults antecedent to this time are important because they affect the course of fluids in the crust (refer to section 3.1.2) and have an effect on subsequent fault tectonics by forcing releasing and/or constraining bends along strike-slip fault systems due to reactivation. In addition, changes in the far-field stresses during the time of interest have an effect on the behavior of hydrothermal systems.

Figure 2 shows a conceptual model for the time-space evolution of a continental-arc region where the near-surface fault dynamics change from strike-slip tectonics to hyperextension within a far-field driven oblique-slip

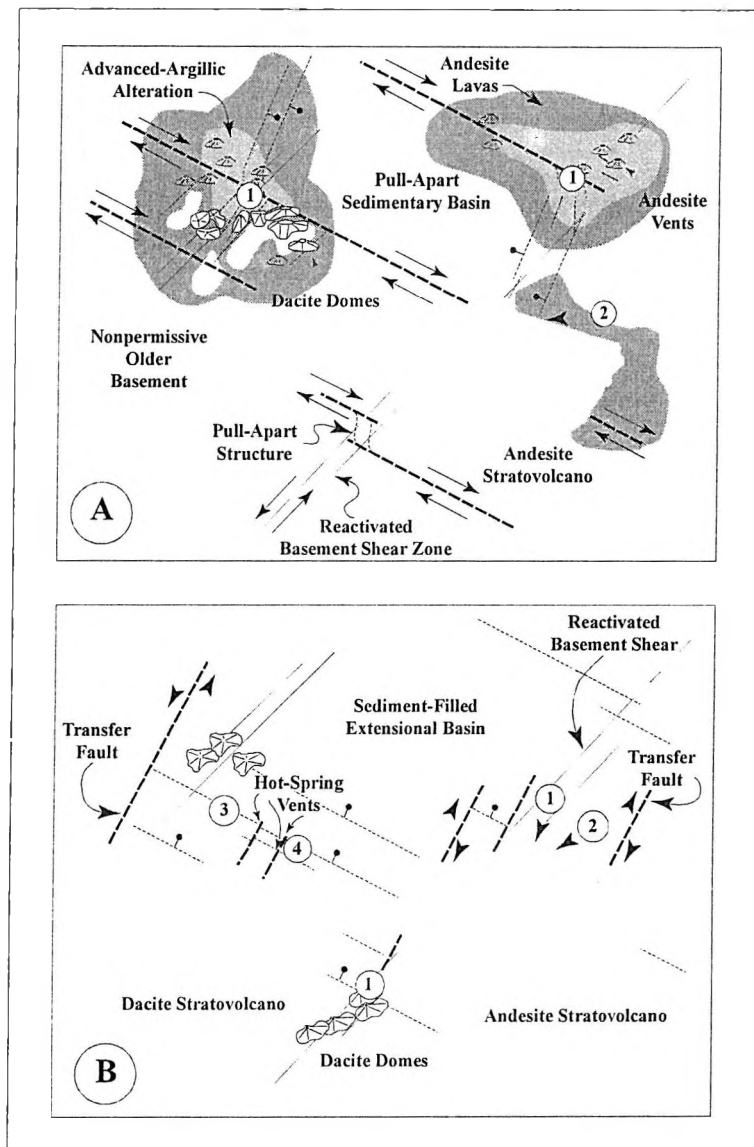


Fig. 2: Hypothetical example of an evolving time-space landscape/dynamics model of a geologic terrane permissive for the occurrence of porphyry- and epithermal-style mineral deposits in a continental-arc setting

**A Stage 1.** Andesitic vents and dacite to rhyodacite domes erupted on a basement that is not permissive for the occurrence of either porphyry- or epithermal-style mineral deposits. Far-field compressive stresses along the tectonic-plate margin led to the development of right-lateral strike-slip faulting (thicker dashed lines) within the magmatic arc. Strain within this terrane was largely accommodated by extension (thinner dashed lines) related to the development of a sedimentary-rock filled pull-apart basin. Releasing bends for the extensional stepovers were forced by reactivation of antecedent basement shear zones (gray lines). Advanced-argillic alteration (light grey areas) (site #1) associated with domes and small andesitic vents in the transfer zones into the duplexes are favorable for the occurrence of quartz-alunite-kaolinite  $\pm$ pyrophyllite gold deposits. The core of the large andesite stratovolcanic edifice (site #2) is favorable for the occurrence of a porphyry-style and associated vein deposits.

**B Stage 2.** Andesitic volcanism wanes in the large stratovolcano and dacitic volcanism becomes predominant through central-vent eruptions and domes in the southwestern part of the permissive terrane. The predominant faulting changes from strike-slip to normal with extension to the northeast. Volcanic activity is primarily in the footwalls of major normal faults. Hydrothermal convection related to the volcanic activity results in favorability for epithermal vein deposits along northeast-striking transfer faults (thicker dashed lines) (site #1) at both central vent edifices and the dacite-dome complex. There is favorability for porphyry-style deposits associated with the andesite center (site #2) as noted for Stage 1, but the dacite stratovolcanic center isn't considered as favorable because the broad area of normal faulting and extensive intrusive activity cause the region to accommodate the strain through considerable thermoelastic expansion and there is a low strain rate on the dacite magma chamber. Because of lateral hydrothermal flow northeasterly from the dacite stratocone, discharge occurs along the basin margin which migrates progressively to the east as thermoelastic expansion and normal faulting progressed. There is hot-spring Hg favorability in steaming ground surrounding the discharge vents (site #3) and, if a lake occupies the basin, there is favorability for low-grade Au in the lake margin deposits (site #4) if steam condensed in the lake waters which then collapsed across the discharge materials and acid-leached them and effectively upgraded the gold concentrations.

strain field. In Figure 2A, Stage 1, the far-field compressional stresses result in strain accommodation along northwest-striking, right-lateral strike-slip faults and associated secondary and extensional faults. This set is superimposed on a pre-existing system of northeast-striking strike-slip basement shear zones. Motion on the interacting en échelon master strike-slip faults is accommodated across stepovers through linking faults. A resulting pull-apart basin dominates the central part of the landscape depicted. Andesitic volcanic vents are widespread, with a single, large andesitic stratovolcano (Fig. 2A) localized in a releasing bend of the pull-apart basin.

During Stage 2 of the evolving landscape (Fig. 2B), a heated, strain softened shallow crust leads to near-field stresses dominating the surficial tectonics. Hyperextension is superimposed on the far-field compressional dynamics. Stretching of a rheologically uniform medium permits low-angle extensional detachments to develop. The northwest-striking faults, formerly strike-slip, serve as headwalls for the extensional detachments and continued basin evolution, and the basement shear zones which controlled the development of the extensional duplex in Stage 1 now control the localization of transfer faults.

During Stage 2, volcanism continues at the Stage 1 stratovolcano in the southeast, and a large dacitic stratoncine grows in the footwall facing the extending basin. Magma-driven thermoelastic stresses are normal to the vertical volcanic feeders; therefore, considerable strain is accommodated and the volcanic edifices are primarily in the footwalls of the normal faults. The andesitic to dacitic volcanoes in Figure 2B are localized within the footwalls of northwest-striking normal faults.

### 3.2.2. Implications of the hypothetical model for mineral-resource assessment

Empirically, we have found that epizonal mineral deposits are most frequently localized within fault systems in zones of releasing and restraining offsets along strike-slip faults and on transfer faults within extensional regimes. This information may be applied to conceptualizations of geothermal systems that might be expected to occur in the two landscape stages in figures 2A and 2B. Figure 3 illustrates a possible model construct for the occurrence of porphyry, epithermal vein, and hot-spring styles of mineralization related to near-neutral pH fluids (adularia stable) in the Figure 2A-B landscape. In the model the predominant hydraulic conductivity is assumed to lie in the plane of the page, and topography and prevailing winds and storms have been positioned such as to result in flow from left to right. Two synhydrothermal stress axes orientations acting on a fault in the plane of the figure are given [(a) and (b)]. Stress axes (a) imply that extension would occur on the fault whereas stress axes (b) imply the fault to be under shear. The hypothetical mineral-resource potential for each of these stress axes orientations is given in Table 3.

The critical thing that integrating dynamics into the landscape evolution brings to assessment is that there is a possibility that both the localization of deposits and likely economic outcomes may be predictable. In the scenario given above, the potential changes with time. For example, from the conceptual model in Figure 3 we predict that the large andesite stratovolcano (Fig. 2A), which is situated at the releasing bend along a northwest-striking master right-lateral, strike-slip fault, is a likely geologic setting for the occurrence of epithermal quartz-adularia-illite vein deposits and possibly porphyry-style deposits along the fault in the plane of the figure. Regarding the epithermal vein potential, however, the predominant flow in the Stage 1 landscape would be to the northeast on highly permeable, long length-scale normal faults (Fig. 3) under stress scenario (a). Highly permeable normal faults disperse rather than focus fluid flow because there are more ways for heat to be shared among randomly moving heated molecules over large volumes than ways for the energy to be restricted to a small region within the permeable zone. In such situations, one should look for higher grade ore bodies in transfer fault zones or on short length-scale normal faults. During Stage 2 (Fig. 2B) the andesite volcano is still active and hydrothermal activity continues. The flow is still along the same fracture network because the far-field  $\sigma_1$  is still oriented the same, but the total mass flux is less dispersed. With the change to stress scenario (b) (Fig. 3), what was formerly a normal fault is now a strike-slip transfer fault. High permeability areas along the structure are now limited; therefore, the same mass flux is redirected through a much smaller volume of rock. It is focused. The coupling of chemical transport and mechanical deformation in the constrained volume is more conducive to rapid and more abundant mineral precipitation. Consequently, during this stage, we might predict that higher grade ores are likely to be superimposed on the earlier low-grade to economically barren vein.

In contrast, the dacite stratovolcano in Stage 2 (Fig. 2B) is constructed in the footwall of what is now a normal fault and flow is along a northeast-striking, transfer structure [Fig. 3, stress scenario (b)] and higher grade vein potential exists along this trajectory. Thus, both volcanoes have comparable potential to produce economic vein deposits, but it was the important shift in stress regimes from Stage 1 to Stage 2 that made the potential of the andesite center comparable to the dacite center. Both hypothesized hydrothermal systems discharge into a basin that may contain a lake. Although not illustrated, if a lake exists, then the condensation of acid volatiles from geother-



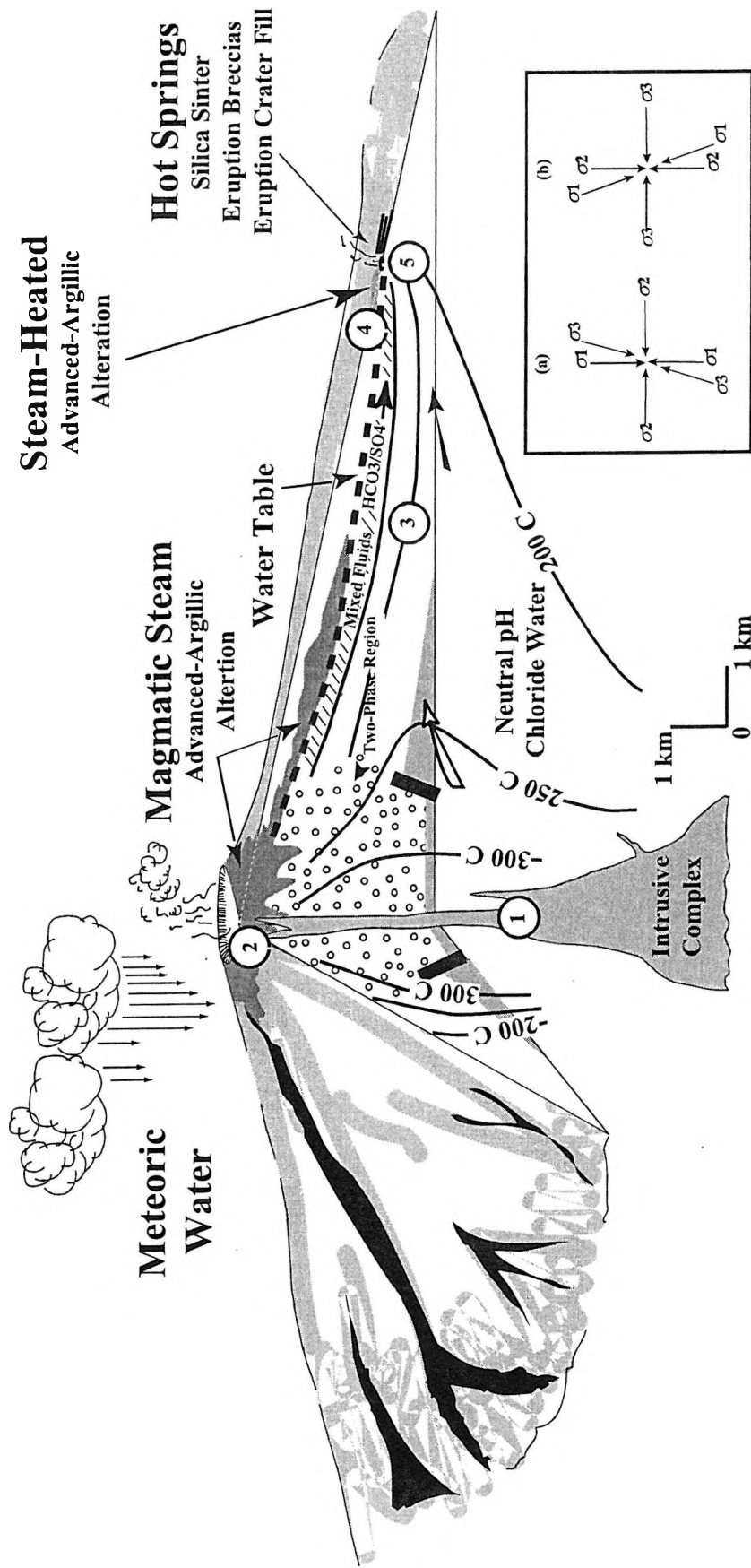


Fig. 3: Conceptual model of flow patterns within and surrounding an upwelling, near-neutral pH geothermal fluid within and adjacent to a stratovolcanic edifice. Prevailing winds are depicted as blowing from left to right; therefore climatic, rainfall, and topographic effects result in lateral flow from left to right. The amount of lateral flow is proportional to the height and slope angle of the volcanic edifice. Five styles of mineralization are depicted: 1. porphyry, 2. magmatic-steam advanced-argillic; 3. epithermal veins; 4. steam-heated hot-spring Hg; and, 5. hot-spring-related Au-Ag. Two different principal stress orientations are shown in (a) and (b). The axes are oriented to indicate the possible stresses acting on the plane of fractures controlling the left to right fluid flow; i.e., in the plane of the cross section. The favorability for the 5 styles of mineralization for the two stress orientations is given in Table 3.

**Table of hypothetical favorabilities for the occurrence of porphyry-, epithermal vein-, and hot-spring-style mineralizations from near-neutral pH fluids associated with stratovolcanoes**

*Table 3*

1. Stage 1 landscape

Landform/Deposit Style	Stress Orientation (a)	Stress Orientation (b)
<b>Andesite Stratovolcano</b>		
Porphyry-style	The favorability is low if the strain rate acting on the volcanic edifice is low.	The favorability is high if the strain rate acting on the volcanic edifice is high.
Epithermal-style veins	The favorability for higher grade veins is low due to unfocused flow on highly permeable NE normal faults.	The favorability for higher grade veins is high due to focused flow on NE transfer faults.
Hot-spring Hg	The favorability is high if steam-heated zone is well developed.	The favorability is high if steam-heated zone is well developed.
Hot-spring Au-Ag	The favorability for higher grade mineralization is high if flow was restricted to small rock volumes due to extensive brecciation and favorable fracture patterns. The favorability for lower grade ores is high under all circumstances.	The favorability for higher grade mineralization is high if flow was restricted to small rock volumes due to extensive brecciation and favorable fracture patterns. The favorability for lower grade ores is high under all circumstances.
Climate-controlled hot-spring Au-Ag	The favorability for low-grade deposit is high if basin occupied by lake with fluctuating surface and water table sufficiently low to produce large steam flow in discharge area.	The favorability for low-grade deposit is high if basin occupied by lake with fluctuating surface and water table sufficiently low to produce large steam flow in discharge area.

2. Stage 2 landscape

<b>Andesite Stratovolcano</b>		
Porphyry-style	In regions undergoing rapid extension, the strain rate is generally low on the magma chamber. The favorability is low if the strain rate in the magma chamber is low.	In regions undergoing rapid extension, the strain rate is generally low on the magma chamber. The favorability is low if the strain rate in the magma chamber is low.
Epithermal-style veins	The favorability for higher grade veins is low due to unfocused flow on highly permeable NW normal faults.	The favorability for higher grade veins is high on NE-striking fractures because the flow is focused.
Hot-spring Hg	The favorability is high if steam-heated zone is well developed.	The favorability is high if steam-heated zone is well developed.
Hot-spring Au-Ag	The favorability for higher grade mineralization is high if flow was restricted to small rock volumes due to extensive brecciation and favorable fracture patterns. The favorability for lower grade ores is high under all circumstances.	The favorability for higher grade mineralization is high if flow was restricted to small rock volumes due to extensive brecciation and favorable fracture patterns. The favorability for lower grade ores is high under all circumstances.
Climate-controlled hot-spring Au-Ag	The favorability for low-grade deposit is high if basin occupied by lake with fluctuating surface and water table sufficiently low to produce large steam flow in discharge area.	The favorability for low-grade deposit is high if basin occupied by lake with fluctuating surface and water table sufficiently low to produce large steam flow in discharge area.
<b>Dacite Stratovolcano</b>		
Porphyry-style	In regions undergoing rapid extension, the strain rate is generally low on the magma chamber. The favorability is low if the strain rate in the magma chamber is low.	In regions undergoing rapid extension, the strain rate is generally low on the magma chamber. The favorability is low if the strain rate in the magma chamber is low.
Epithermal-style veins	The favorability for higher grade veins on NW-striking fractures is low due to unfocused flow.	The favorability for higher grade veins on NE transfer structures is low due to no reactivated underlying basement shear.
Hot-spring Hg	The favorability is high if steam-heated zone is well developed.	The favorability is high if steam-heated zone is well developed.
Hot-spring Au-Ag	The favorability for higher grade mineralization is high if flow was restricted to small rock volumes due to extensive brecciation and favorable fracture patterns. The favorability for lower grade ores is high under all circumstances.	The favorability for higher grade mineralization is high if flow was restricted to small rock volumes due to extensive brecciation and favorable fracture patterns. The favorability for lower grade ores is high under all circumstances.
Climate-controlled hot-spring Au-Ag	The favorability for low-grade deposit is high if basin occupied by lake with fluctuating surface and water table sufficiently low to produce large steam flow in discharge area.	The favorability for low-grade deposit is high if basin occupied by lake with fluctuating surface and water table sufficiently low to produce large steam flow in discharge area.

Favorability is given for two different orientations of the stresses acting on the potentially mineralized fracture systems linked to the evolving landscape model in figures 2A and 2B.

mal steam in the lake waters may alter the discharge deposits and effectively upgrade them through acid leaching and redeposition to form a low-grade epithermal deposit at the lake water interface along the discharge zone. Adding such changes to the geologic setting changes the mineral-resource potential.

The porphyry-style mineralization potential is not equivalent for both stratovolcanoes in Figure 2. A constraint is imposed by the fault dynamics. The andesite stratovolcano is exposed to both Stage 1 and Stage 2 dynamics whereas the dacite stratovolcano is exposed only to Stage 2 dynamics. There is a higher potential for porphyry-style mineralization within the andesite edifice during the Stage 1 period than in the dacite stratovolcano of Stage 2. The andesite was initially constructed in a releasing bend where the maximum stress is focused, the total stress exceeds the far-field maximum principle stress, and the stress gradient is steepest (cf. SEGALL and POLLARD, 1980). All porphyries we have examined empirically were formed along strike-slip fault systems and most formed in such releasing bends (the remainders were in constraining bends). The dacite stratovolcano was constructed along an extensional fault zone where the stress overall would be lower than the far-field maximum principal stress. Fluids would be dispersed rather than being focused as in releasing bends of strike-slip faults reducing the expectation for deposit development.

### 3.3. Quantified mineral-deposit model attributes

To make deposits have a more predictive capability, two approaches are possible. The first approach is based on the observed frequency of occurrence of attributes of all deposit types consistent with the USGS models such as specific minerals, rock types, and associated deposit types. The second approach is the development of "metrics" that may be used to estimate the probabilities of occurrence of deposits as well as the different types of genetically associated deposits (DREW and MENZIE 1993).

#### 3.3.1. Frequency of occurrence of deposit attributes

Linking observed frequency of deposit attributes to existing deposit models allows for the objective solution of several problems in quantitative resource assessment. Descriptive models in COX and SINGER (1986) have two parts. The first describes the geologic environments in which the deposits are found; the second gives the identifying characteristics of the deposits. Thus, the first part plays a primary role in the delineation process in that it describes the general geologic setting favored by a deposit type. The second part of the descriptive model helps classify known deposits and occurrences into types which can also aid in the delineation process. In some cases, geologic environments not shown on geologic maps can be identified by the types of known deposits and occurrences present.

Both quantitative and non-quantitative resource assessments require the integration of different kinds of geoscience information. A key kind of information is the classification of known deposits and occurrences in the region. In all assessments made to this day, these classifications have been subjective. The physical attribute data tabulated in the second part of the descriptive deposit model are the most appropriate quantities for this task. In a large independent test of a probabilistic neural network's ability to classify more than 2500 deposits and occurrences into 28 deposit types, SINGER and KOUDA (in press) demonstrated that mineralogy and six rock types can be used to classify the deposits into generalized groups, but not sufficient for classification into specific deposit types. These tests also showed that additional spatial information would increase the likelihood of properly classifying mineral occurrences that have sparse attribute information.

Quantifying attributes of geologic environments offers the possibility of objectively integrating different kinds of information such as that in GIS systems. Wherever spatial data such as rock types and associated deposit types prove to be predictive, it should be possible to quantitatively integrate GIS information into the classification process and link GIS data to mineral deposit models. These quantitative attributes could then be used in the identification and classification of permissive terranes in resource assessments. As noted by SINGER (1993b), data are also needed on barren areas to properly classify the population of possible mineralized environments.

Databases have already been gathered for selected attributes in a number of deposit types. MOSIER et al. (1986) compiled a comprehensive database on epithermal Au-Ag deposits, MOSIER et al. (1983) prepared one on volcanic-rock hosted massive sulfide deposits, and SINGER (1997) compiled an extensive database of minerals from a large number of deposit types. Table 4 gives an example of a small part of a quantitative mineral-deposit model.

### 3.3.2. Metrics that predict associated (linked) deposit types

Spatial associations of certain deposit styles have led to the long-standing concept among economic geologists of deposit zoning and associated deposit types. At the root of zoning is the assumption that hydrothermal ore deposits have magmatic origins (cf. LINDGREN 1933). Associated deposit types are typically viewed as a geochemical process, with the patterns resulting from solubility, pressure, and temperature gradients along some fluid path-line (cf. GUILBERT and PARK 1986). DREW and MENZIE (1993) and DREW (1997) suggested that a “metric”—an ordered set of occurrence probabilities specified by a set of inequalities—for zoning patterns and associated deposit types may be calculated. Working from interpretations of metallogenic information from which a density of deposits within a well-explored district or region may be calculated, they argue that within a permissive tract, each associated deposit type occurs according to some metric. Establishing such metrics is important to making deposit models more quantitative.

## 4. CONCLUSIONS

The outcomes resulting from mineral-resource assessments for land-use and economic development purposes are policy decisions. Therefore, assessment methodologies should be guided by the needs of policy analysis and not the whimsy of scientists. We believe that scientific research on the components of assessments, such as mineral-deposit modeling, must lead to assessment outputs that provide scientifically valid information for policy makers to consider alternative policies. In this paper, we have taken the position that quantification of attributes in mineral-deposit models is one such direction in which model development should be taken, because quantitative models contribute to more precise predictions of undiscovered resources and more precision in estimating the uncertainties in such estimates.

Because the full dimension of components in mineral-deposit models are needed to be effective, we have suggested that approaches to quantify terrane characteristics, mineral-district characteristics, and deposit characteristics should be explored, particularly in the context of the fundamental principles important in ore-forming processes.

**Percentage of mineral deposits of a given type (rows) with specific minerals (columns) within them (from SINGER et al., 1997, based on models of COX and SINGER, 1986)**

*Table 4*

Deposit Type	Mineral													
	Adularia	Bornite	Cinnabar	Chalcopyrite	Gold	Enargite/Luzonite	Galena	Kaolinite/Illite/Dickite	Molybdenite	Native Hg	Pyrite	Sericite	Sphalerite	Stibnite
Porphyry Cu (17, 141)	1	83	1	100	37	21	46	45	84	0	100	94	54	2
Porphyry Cu-Au (20c, 24)	0	96	0	100	50	17	46	42	71	0	100	96	46	0
Polymetallic Replacement (19a, 29)	3	31	14	100	48	38	97	28	24	0	93	55	93	21
Hot-Spring Au-Ag (25a, 16)	75	6	56	38	94	6	38	100	13	6	88	63	31	50
Creede Epithermal Vein (25b, 25)	32	32	8	68	60	40	88	40	8	0	80	44	100	24
Comstock Epithermal Vein (25c, 68)	65	25	9	81	87	4	69	31	10	0	84	35	63	18
Sado Epithermal Vein (25d, 29)	28	7	3	72	86	7	41	38	0	0	90	45	41	17
Epithermal quartz-alunite Au (25e, 33)	9	45	15	64	91	91	61	91	9	3	97	36	67	15
Hot-Spring Hg (27a, 39)	0	0	100	0	5	0	5	3	0	10	41	0	0	5

In parentheses next to each deposit type is the COX and SINGER (1986) model number followed by the number of deposits analyzed.

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