Chapter A

INTRODUCTION TO GEOENVIRONMENTAL MODELS OF MINERAL DEPOSITS

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INTRODUCTION

Since the beginning of economic geology as a subdiscipline of the geological sciences, economic geologists have tended to classify mineral deposits on the basis of geological, mineralogical, and geochemical criteria, in efforts to systematize our understanding of mineral deposits as an aid to exploration. These efforts have lead to classifications based on commodity, geologic setting (Cox and Singer, 1986), inferred temperatures and pressures of ore formation (Lindgren, 1933), and genetic setting (Park and MacDiarmid, 1975; Jensen and Bateman, 1979). None of these classification schemes is mutually exclusive; instead, there is considerable overlap among all of these classifications. A natural outcome of efforts to classify mineral deposits is the development of "mineral deposit models". A mineral deposit model is a systematically arranged body of information that describes some or all of the essential characteristics of a selected group of mineral deposits; it presents a concept within which essential attributes may be distinguished and from which extraneous, coincidental features may be recognized and excluded (Barton, 1993). Barton (1993) noted that the grouping of deposits on the basis of common characteristics forms the basis for a *classification*, but the specification of the characteristics required for belonging to the group is the basis for a *model*. Models range from purely descriptive to genetic. A genetic model is superior to a descriptive model because it provides a basis to distinguish essential from extraneous attributes, and it has flexibility to accommodate variability in sources, processes, and local controls. In general, a descriptive model is a necessary prerequisite to a genetic model.

DEFINITION OF A GEOENVIRONMENTAL MODEL

Geoenvironmental models are natural extensions of mineral deposit models. Plumlee and Nash (1995) defined a geoenvironmental model of a mineral deposit as a compilation of geologic, geochemical, geophysical, hydrologic, and engineering information pertaining to the environmental behavior of geologically similar mineral deposits (1) prior to mining, and (2) resulting from mining, mineral processing, and smelting. Thus, a geoenvironmental model provides information about natural geochemical variations associated with a particular deposit type, and geochemical variations associated with its mining effluents, wastes, and mineral processing facilities, including smelters. Data include information about waters and solids.

From a practical perspective, a geoenvironmental model provides an opportunity to assemble information traditionally within the realm of the economic geologist, and recast it in an "environmentally friendly" format, minimizing the jargon commonly used by economic geologists or mining engineers. Likewise, a model also provides the opportunity to assemble information traditionally outside the realm of the economic geologist, such as water chemistry data, and biologic impact criteria. For both purposes, a major goal is to establish cause-and-effect linkages among the geologic attributes of a deposit, its environmental setting, its mining history (or future), and its environmental behavior. Such information should prove beneficial to (1) environmental scientists interested in mitigating potential environmental problems associated with proposed mines, (2) environmental scientists interested in remediating existing problems at abandoned mine sites, (3) land-use planners that are involved in permitting proposed mines or reclaiming abandoned mine lands, and (4) industry interested in mine planning and mineral exploration.

ANATOMY OF A GEOENVIRONMENTAL MODEL

Geoenvironmental models provide a variety of information about the geological and geochemical setting of mineral deposits, mining and mineral processing technology as they relate to the generation of mine waste, and the environmental behavior of mineral deposits in the broadest sense. Brief descriptions of key elements of a geoenvironmental model, which have been modified from Plumlee and Nash (1995) and du Bray (1995), are presented below. Plumlee (1999), and Plumlee and others (1999) have discussed many of the salient features of these categories. Each mineral deposit is unique unto itself, and each class of mineral deposit is also unique. Therefore, some degree of flexibility must be maintained in the features considered essential for a given model. Thus, this list is not necessarily considered comprehensive.

Deposit Type

The classification of the deposit is the basis for comparisons of the factors that contribute to variations in potential environmental impact. Several levels of classification for a deposit type may be available that shed additional insights into geochemical signatures and environmental behavior. As with any attempt at classification, controversy may exist over which are the defining characteristics. Therefore, specific examples of deposits that belong to a class are essential for clarifying intent in classification. One useful way to look at the classification of mineral deposits is to consider it in terms of a matrix of the major commodity produced (i.e., Cu, Zn, Pb, Au, or Ag), and ore and host rocks characteristics (Table 1). The latter has important geotechnical implications for environmental impact in terms of acid-generating potential and acid-neutralizing capacity. This matrix approach highlights the strength of geoenvironmental models, because it provides a framework on which to overlay insights from the genetic attributes of the individual deposit types.

Related Deposit Types

Mineral deposits are manifestations of parts of larger, complex geochemical systems. Thus, other parts of these complex systems may manifest themselves as different types of mineral deposits, which will probably behave differently in the environment and present different potential environmental problems. For example, there is a common association of seafloor base- and precious-metal massive sulfide deposits with low-sulfide quartz-gold vein ("Mother Lode") deposits. Massive sulfide deposits commonly have associated acid drainage problems due to their abundant pyrite contents, whereas low-sulfide quartz-gold vein deposits do not. However, mercury amalgamation historically was a common technique used to concentrate gold from these ores. In watersheds that contain both types of deposits, constructed wetlands used to remediate acid drainage problems could exacerbate mercury problems by providing a reducing environment to promote mercury methylation. Thus, awareness of potentially associated deposit types and their attributes has important environmental implications.

Deposit Size

The size of deposits can vary by several orders of magnitude. For seafloor massive sulfide deposits, a single deposit may lie within the watershed of a small perennial stream, whereas for porphyry copper deposits, a single deposit can span several watersheds.

Host Rocks

The mineralogy and geochemistry of the host rocks are especially important in terms of the acid-generating or acid-neutralizing potential of a mineable rock package. The host rocks of a mineral deposit can also serve to naturally elevate background aqueous contributions of acidity and metals. For example, the unmineralized sulfidic schists of the Anakeesta Formation, which host the Fontana and Hazel Creek massive sulfide deposits in North Carolina, naturally generate acidic waters, which locally exceed water quality guidelines for zinc and other dissolved elements; the water quality of adjacent watersheds underlain by sandstone or carbonates is well within all standards for aquatic health (Seal and others, 1998).

Surrounding Geologic Terrane

Mineral deposits form in specific geologic settings, which have certain predictable geochemical attributes. Thus, even though the immediate host rocks of a deposit are devoid of carbonate rocks, such as those associated with "Besshi-type" massive sulfide deposits, the larger scale package of rocks can contain significant amounts of limestone and (or) dolomite, which can serve to increase the alkalinity and hardness of watersheds receiving acid drainage from these types of deposits. Also, the structural setting of the deposit can greatly influence the distribution of fractures and associated permeability.

Wall-Rock Alteration

Wall-rock alteration typically changes the chemistry of the host rock for a significant distance away from the ore zones. Alteration may increase the acid-neutralizing capacity of a rock by introducing carbonate minerals, or it can decreasing the acid-neutralizing capacity of a rock by transforming feldspars into clay minerals.

Nature of Ore

The nature of the ore affects the potential intensity of adverse environmental effects and the amenability to various mining methods. The potential environmental behavior of a small tonnage, massive sulfide deposit is obviously quite different from a large tonnage porphyry copper deposit, which is characterized by disseminated sulfide minerals that average only a few percent of the rock. For example, the ore from massive sulfide deposits typically comprises greater than 50 percent pyrite and (or) pyrrhotite, and a few percent of chalcopyrite, sphalerite, and galena. The chalcopyrite, sphalerite, and galena are recovered for their economic value, but most of the pyrite and pyrrhotite end up in waste piles. At historic mines, the iron-sulfide wastes were discarded with little regard for potential environmental effects. In contrast, typically porphyry ores comprise just a few percent of total sulfide minerals. Also, the mineable tonnage of a typical porphyry deposit is at least an order of magnitude larger than a typical massive sulfide deposit, thus generating more waste material.

Table 1. Selected mineral deposit types arranged by primary commodity and ore/host rock characteristics

	Ore/Host Rock Characteristics			
	Massive/Silicate	**Disseminated/Silicate**	**Massive/Carbonate**	**Disseminated/Carbonate**
Primary Commodity				
Gold		•Adularia-sericite epithermal veins •Epithermal quartz-alunite Au •Carlin-type Au •Low-sulfide quartz-gold veins •Au-Ag telluride veins	•Skarn	•Carlin –type Au
Silver	•Sedimentary-exhalative	•Adularia-sericite epithermal veins •Polymetallic veins Au-Ag telluride veins	•Skarn •Manto-type	
Copper	•Cyprus-type •Besshi-type •Noranda-type •Magmatic Ni-Cu	•Porphyry •Sediment-hosted Cu	•Skarn	
Lead	•Bathurst-type •Kuroko-type •Sedimentary-exhalative		•Mississippi Valley-type •Manto/skarn	
Zinc	•Sedimentary-exhalative •Kuroko-type •Bathurst-type		•Mississippi Valley-type •Manto/skarn	
Mercury	•Silica-carbonate Hg	•Almaden Hg •Silica-carbonate Hg	•Silica-carbonate Hg	•Silica-carbonate Hg

Deposit types are based on Cox and Singer (1986) and du Bray (1995).

Mining and Ore Processing Methods

Mining and ore-processing methods are influenced by the geology of the deposit. The hydrologic differences between underground and open pit mines are significant. Evaporative concentration is more prominent in open pit settings. With regards to abandoned mines, historic evolution of ore beneficiation techniques can cause different “vintages” of mine wastes to be variably endowed in metals. Flotation circuits and cyanide leach operations add exotic chemicals to mine wastes. Historical use of mercury amalgamation to process gold ores is a major source of mercury contamination at abandoned mine sites.

Deposit Trace Element Geochemistry

Most deposits are exploited for just a few (or less) primary commodities, yet they can have numerous other potentially toxic elements present in subeconomic quantities. Cadmium is rarely recovered as primary commodity, even though is ubiquitously found substituting for zinc in sphalerite. Similarly, arsenic is common in many deposit types as a solid solution in pyrite or as arsenopyrite. Both pyrite and arsenopyrite are typically discarded in waste. Thus, knowledge of the trace element geochemistry of a deposit is essential for assessing all of the potential environmental impacts.

Primary Mineralogy and Zonation

The primary, or original mineralogy of mineral deposits is the ultimate source of metals, acidity, and, in some cases, alkalinity in these systems. In addition, many hydrothermal mineral deposits are zoned. For example, porphyry copper systems can contain significant amounts of lead and zinc. However, the lead- and zinc-rich zones are typically found peripheral to the copper-rich centers of these deposits, and consequently, are rarely mined. Also, the presence of pyrite, as a source of dissolved ferric iron, greatly enhances the acid-generating potential of weathering monosulfide minerals like sphalerite or galena (Plumlee, 1999). The weathering behavior of minerals can vary significantly due to differences in morphological characteristics and trace element compositions. For example, sedimentary environments can contain "framboidal" pyrite, which is much more reactive than cubic crystals of pyrite. Likewise, pyrite that contains significant amounts of arsenic oxidizes more rapidly than arsenic-free pyrite (Plumlee, 1999).

Secondary Mineralogy

The secondary mineralogy, which forms through the weathering of a deposit or its mine wastes, tends to sequester metals and (or) acidity on either a long-term or short-term basis. Hydrated ferric oxides can sorb metals on a somewhat refractory substrate, whereas efflorescent metal sulfate salts, such as melanterite, serve as a means to store metals and acidity on a temporary basis during dry periods. These salts readily dissolve during rain storms or spring snow melt and deliver their metals and acidity to the surrounding watershed. For many deposit types, pre-mining oxidation of primary ores was a major contributing factor in enriching some deposits to economic grades.

Soil and Sediment Signatures

Pre-mining soil and stream sediment signatures may be useful for establishing pre-mining backgrounds. Also, soils around abandoned mine and smelter sites represent a significant sink for metals.

Topography and Physiography

Topography and physiography are important factors controlling the local hydrologic setting, particularly the location of the water table. Also, deposits located in physiographic provinces in the rain shadow of orographic highs, such as the Great Basin of Nevada east of the Sierra Nevada Mountains, will behave quite differently than those located in provinces with high rainfall.

Hydrology

The hydrologic setting, especially relative to the water table, is a key variable in determining the magnitude of mine drainage problems. The Iron Mountain mine in northern California is dominantly situated above the water table and produces waters with pH values as low as –3.6 (Nordstrom and others, 2000), whereas much of the Penn mine is below the water table and only produces waters with pH values as low as 2.8 (Alpers and others, 1999). Similarly, the geologic setting of a deposit can influence the distribution of fracture-controlled permeability, and thus, access to ground water.

Drainage Signatures

The geology of a deposit exerts a major influence on both pre-mining background water compositions and on mine drainage. Drainage characteristics vary systematically according to deposit type (Fig. 1). Increases in total dissolved base metals generally correlate with increases in associated pyrite content, decreases in acid-neutralizing capacity, and increases in base metal content of deposits (Plumlee, 1999).

Climatic Effects

Climate plays a key role in the environmental behavior of mineral deposits. Differences in temperature, amount of precipitation, and humidity are probably the most important climatic variables (Plumlee, 1999). Temperature and humidity are the prime variables that control evaporation. Evaporation limits the amount of water in semi-arid to arid climates. Evaporation can concentrate solutes in all climates. Winter freezing conditions can lead to seasonally episodic fluctuations in drainage chemistry. Ecosystems may form a reasonable basis for assessing the role of climatic variability in the environmental behavior of mineral deposits (Bailey, 1996). Nevertheless, more research is needed to better understand the link between climate and the environmental impacts of mineral deposits.

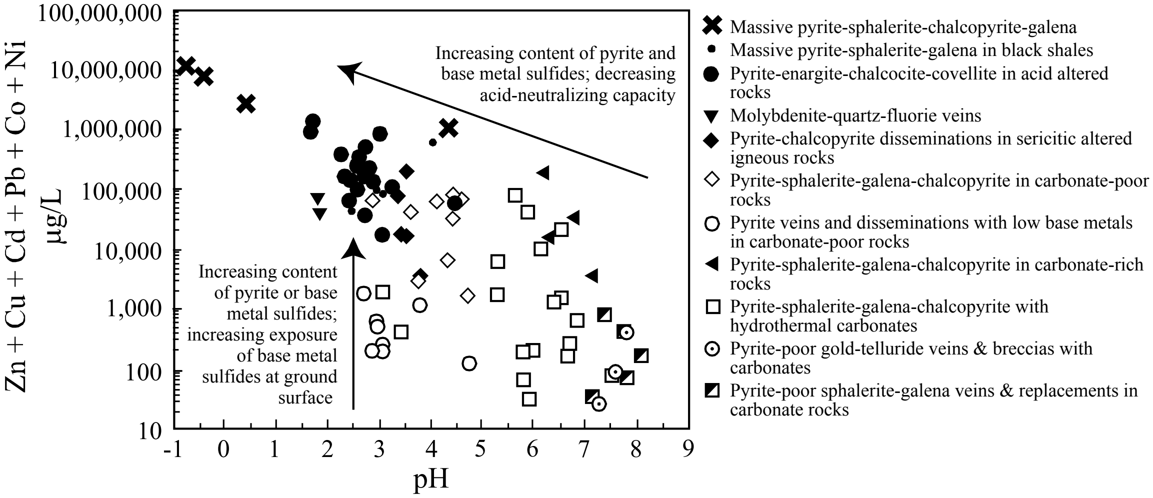

Figure 1. Ficklin plot of the sum of the base metals Cd, Co, Cu, Ni, Pb, and Zn versus pH illustrating the variation of mine drainage chemistry as a function of the geologic characteristics (type) of specific mineral deposits. Modified from Plumlee and Nash (1995), and Plumlee (1999).

Potential Environmental Concerns

Potential environmental concerns associated with mineral deposits can generally be divided into three broad categories: (1) human health risks; (2) ecosystem risks; and (3) physical hazards. All of these concerns are ultimately rooted in the geologic foundation of the mineral deposit. Human health risks (exclusive of physical hazards) generally focus on metals (lead, arsenic, selenium, and mercury) associated with various mineral deposit types, and elements and compounds used in ore processing, such as mercury or cyanide. Ecosystem risks are associated with acidity and a range of metals. Physical hazards, such as open shafts and open pits, are related to the mining required to exploit specific mineral deposit types.

THE STATE OF THE ART AND SCOPE

In their present form, geoenvironmental models are largely descriptive in nature. They represent empirical compilations of data that provide a powerful predictive capability of possible ranges of environmental impact. Du Bray (1995) presented preliminary geoenvironmental models for 32 different mineral deposit types. Geoenvironmental model research at the U.S. Geological Survey since 1995 has tended to concentrate on a more limited number of deposit types. The emphasis has been placed on deposit types that are currently attractive exploration targets and (or) historically environmentally problematic (or both!). Future efforts are expected to develop quantitative genetic geoenvironmental models.

In their present form, geoenvironmental models can serve several purposes including: (1) the establishment of premining baseline conditions for mines, inactive, active, and planned; (2) the improvement of mine planning and development by better anticipating and mitigating potential environmental problems; (3) the improvement of remediation at abandoned mine sites by outlining the spectrum of potential problems that might be encountered at a site; and (4) the assessment of abandoned mine lands issues by providing a tool for identifying, prioritizing, and planning remediation efforts (Plumlee and Nash, 1995). In spite of their power, geoenvironmental models should not be used to predict absolute pH and metal concentrations that will develop at a particular site, nor should they be used in place of thorough field studies to characterize sites (Plumlee, 1999). Instead, they are best used as guidelines for potential ranges of environmental signatures that may apply to the site.

The material presented in this report has been previously presented as a short course titled "Geoenvironmental Analysis of Ore Deposits" at the 5th International Conference on Acid Rock Drainage (ICARD) held in Denver, Colorado on May 21, 2000. The remainder of this volume is organized first to present brief summaries of basic concepts of the geochemistry of solids (Hammarstrom and Smith, 2002) to ensure that the reader has a minimum background in geochemical concepts that are fundamental to geoenvironmental models. Next, a summary of rapid screening techniques to assess the potential impact of mine wastes is presented (Smith and others, 2002). Finally, individual models will be presented in formats that range from case studies of specific deposits to national and global syntheses. Deposit types include porphyry deposits (Tuttle and others, 2002), polymetallic vein deposits, emphasizing the Couer d'Alene district, Idaho (Balistrieri and others, 2002), carbonate-hosted deposits (Foley, 2002a,b; Hammarstrom, 2002; Kirk and Kirk, 2002), mercury associated with epithermal deposits (Rytuba, 2002), lode gold deposits (Ashley, 2002), and massive sulfide deposits (Seal and others, 2002).

REFERENCES CITED

Alpers, C.N., Hamlin, S.N., and Hunerlach, M.P., 1999, Hydrogeology and geochemistry of acid mine drainage in ground water in the vicinity of Penn mine and Camanche reservoir, Calaveras County, California: summary report, 1993-95: U.S. Geological Survey Water-Resources Investigations 96-4287, 59 p.

Ashley, R.P., 2002, Geoenvironmental model for low-sulfide gold-quartz vein deposits, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 176-195.

Bailey, R.G., 1996, Ecosystem Geography: Springer, New York, 241 p.

Balistrieri, L.S., Box, S.E., and Bookstrom, A.A. 2002, A geoenvironmental model for polymetallic vein deposits: A case study on the Coeur d'Alene mining district and comparisons with drainage from mineralized deposits in the Colorado mineral belt and Humboldt basin, Nevada, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 143-160.

Barton, P.B., Jr., 1993, Problems and opportunities for mineral deposit models, *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., Mineral Deposit Modeling: Geological Association of Canada, Special paper 40, p. 7-13.

Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.

du Bray, E.A., ed., 1995, Preliminary compilation of descriptive geoenvironmental mineral deposit models: U.S. Geological Survey Open-File Report 95-831, 272 p.

Foley, N.K., 2002a, Environmental geochemistry of platform carbonate-hosted sulfide deposits, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 87-100.

Foley, N.K., 2002b, A geoenvironmental lifecycle model: The Austinville platform carbonate deposit, Virginia, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 101-107.

Hammarstrom, J.M., 2002, Environmental geochemistry of skarn and polymetallic carbonate-replacement deposit models, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 115-142.

Hammarstrom, J.M., and Smith, K.S., 2002, Geochemical and mineralogic characterization of solids and their effects on waters in metal-mining environments, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 8-54.

Jensen, M.L., and Bateman, A.M., 1979, Economic Mineral Deposits: 3rd edition, John Wiley and Sons, New York, 593 p.

Kirk, L.B., and Kirk, A.R., 2002, A geoenvironmental mineral deposit model for the New World polymetallic replacement/skarn deposit, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 108-114.

Lindgren, W., 1933, Mineral Deposits: 4th edition, McGraw-Hill Book Company, Inc., New York, 930 p.

Nordstrom, D.K., Alpers, C.N., Ptacek, C.J., and Blowes, D.W., 2000, Negative pH and extremely acidic mine waters from Iron Mountain, California: Environmental Science and Technology, v. 34, p. 254-258.

Park, C.F., Jr., and MacDiarmid, R.A., 1975, Ore Deposits: 3rd edition, W.H. Freeman and Company, San Francisco, 529 p.

Plumlee, G.S., 1999, The environmental geology of mineral deposits, *in* Plumlee, G.S., and Logsdon, M.J., eds., The Environmental Geochemistry of Mineral Deposits, Part A: Processes, Techniques, and Health Issues: Reviews in Economic Geology, v. 6A, p. 71-116.

Plumlee, G.S., Smith, K.S., Montour, M.R., Ficklin, W.H., and Mosier, E.L., 1999, Geologic controls on the composition of natural waters and mine waters draining diverse mineral-deposit types, *in* Filipek, L.H., and Plumlee, G.S., eds., The Environmental Geochemistry of Mineral Deposits, Part B: Case Studies and Research Topics: Reviews in Economic Geology, v. 6B, p. 373-432.

Plumlee, G.S., and Nash, J.T., 1995, Geoenvironmental models of mineral deposits – fundamentals and applications: U.S. Geological Survey Open-File Report 95-831, p. 1-9.

Rytuba, J.J., 2002, Mercury geoenvironmental models, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 161-175.

Seal, R.R., II, Hammarstrom, J.M., Southworth, C.S., Meier, A.L., Haffner, D.P., Schultz, A.P., Plumlee, G.S., Flohr, M.J.K., Jackson, J.C., Smith, S.M., and Hageman, P.L., 1998, Preliminary report on water quality associated with the abandoned Fontana and Hazel Creek mines, Great Smoky Mountains National Park, North Carolina and Tennessee: U.S. Geological Survey Open-File Report 98-476, 50 p.

Seal, R.R., II, Hammarstrom, J.M., and Foley, N.K, 2002, Seafloor massive sulfide deposits, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 196-212.

Smith,K.S., Campbell, D.L., Desborough, G.A., Hageman, P.L., Leinz, R.W., Stanton, M.R., Sutley, S.J., Swayze, G.A., and Yager, D.B., 2002, Toolkit for the rapid screening and characterization of waste piles on abandoned mine lands, , *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 55-64.

Tuttle, M., Wanty, R.B., and Berger, B.R., 2002, Environmental behavior of two molybdenum porphyry systems, *in* Seal, R.R., II, and Foley, N.K., eds., Geoenvironmental Models of Mineral Deposits: U.S Geological Survey Open-File Report 02-195, p. 65-86.