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Deposit modeling and mining–induced environmental risks

ENVIRONMENTAL MODELS OF MINERAL DEPOSITS A STATE OF THE ART

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ABSTRACT

Although mineral deposits have been classified by their geologic and mineralogical characteristics for decades, the recognition that mineral deposits also could be classified by their environmental characteristics is relatively new. In the past 5 years, numerous advancements have been made in this subject area, building on the earlier work of economic geologists who classified geologic characteristics. Several different approaches to understanding the environmental behavior of mineral deposits and associated altered areas have been taken, ranging from wholesale assessments of large areas (millions of km^2) to detailed assessments of individual watersheds or individual mines. While these first attempts have succeeded in describing some of the environmental characteristics of ore deposits in a number of ways, many important "environmental variables" are not included in present descriptive models. For example, the models should be expanded in scope to include a more thorough treatment of climatic and ecoregional effects- embodying such physical environmental characteristics as precipitation, evaporation, temperature, and ground water-surface water interactions. More complete model descriptions will have applications to the determination of baselines and natural backgrounds in mined and unmined areas, as well as possible anticipated effects of new mining in a given area, and mitigation and remediation strategies. The challenge to geologists and geochemists is to incorporate a widely disparate set of physical and chemical characteristics of mineralized and altered zones at scales ranging from microscopic (sub-millimeter) to macroscopic (10's to 100's of kilometers). This paper presents an overview of the development of mineral deposit environmental models, the current state of the art, an evaluation of needed improvements, and expected advancements in this field.

1. WHAT IS THE PROBLEM?

It has long been recognized that weathering of sulfide minerals may have deleterious effects on the environment. This is particularly true for mineral deposits which, when exposed to the weathering environment, can produce acidic, sulfate-rich waters capable of transporting harmful concentrations of various heavy metals. The most important mineral in terms of acid generation is pyrite, which reacts with oxygen from the atmosphere according to the following overall reactions (STUMM and MORGAN 1996):

$$FeS_{2(pyrite)} + 3.5O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+, \quad (1)$$

$$\text{and } FeS_{2(pyrite)} + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+. \quad (2)$$

The latter reaction consumes dissolved ferric iron rather than oxygen, so to maintain the reaction, an adequate supply of ferric ions must be present in the system. Lacking a mineral source for Fe^{3+} such as oxidized biotites or chlorites, the ferrous product in reaction 2 must be reoxidized so that reaction 2 can continue to proceed. The oxidation of ferrous iron can be written as:

$$14Fe^{2+} + 3.5O_2 + 14H^+ = 14Fe^{3+} + 7H_2O. \quad (3)$$

Adding reactions 2 and 3 produces reaction 1, so the net reaction of pyrite oxidation follows reaction 1 in either case. Similar reactions can be written for the oxidation of other sulfide-bearing minerals, but pyrite oxidation is generally the predominant acid-generating reaction because pyrite is usually the most common sulfide mineral in a mineralized zone. Other sulfides such as pyrrhotite, chalcopyrite, arsenopyrite, galena, and sphalerite also may generate acid as they oxidize. Because of their generally lower abundance in a body of mineralized rock, the amount of protons produced by the oxidation of the other sulfide-bearing minerals is subordinate to that from pyrite oxidation. When pyrite is oxidized, the acidic waters generated, if not neutralized by reaction with other minerals such as carbonates, may lead to increased mobility of metals such as Fe, As, Cu, Zn, Cd, Cr, Pb, etc. These metals may be present as trace elements in the pyrite (esp. As), or they may be mobilized from other mineral sites.

Oxidation of pyrite and other sulfide-bearing minerals may take place any time these sulfides are exposed to oxygen in the presence of water, whether at the surface or in the shallow subsurface. The rates of the oxidation reactions are enhanced by the action of bacteria (GOULD et al. 1994), which in turn require a moist environment to facilitate their existence. The moisture becomes acidic as the oxidation reaction proceeds, leading to the phenomenon of acidic drainage. The basic requirements for rapid sulfide oxidation, then, are the presence of sulfide, a supply of water and oxygen or ferric iron, and bacteria and their required nutrients.

Acidic drainage may be generated as a natural process or it may result from mining activities. In nature, a deposit exposed at the surface will generate acidic drainage in some amount. The concentration of the acid (measured as pH) is enhanced by increased rates of oxidation, increased rates and amounts of exposure of sulfide-bearing minerals to air, increased bacterial activity (i.e., warmer temperatures, presence of organic material), and, to some extent, decreased water fluxes through the zone of oxidation. The latter is true because if a greater quantity of water flows through the oxidation zone, then the acid will be diluted. In systems with a smaller flux of water, stronger acid concentrations accumulate, resulting in pH's typically in the range of 2-4, but perhaps lower (FICKLIN et al. 1992, NORDSTROM et al. 1979, NORDSTROM 1982, NORDSTROM et al. 1991, PLUMLEE et al. 1992). The rate and amount of exposure of sulfide-bearing minerals to the air may be controlled by the relative rates of mechanical versus chemical weathering (MILLER and MCHUGH in press). Mechanical weathering (erosion) rates are greatest in areas with steep slopes, well-developed fracture networks, and intense freeze/thaw action. In areas where mechanical weathering rates are greatest, fresh sulfide minerals are continually brought to the surface and oxidized, this increased availability of sulfides leads to greater rates of acid production.

1.1. Enhancement of weathering rates by mining

Mining activities may enhance the rate and extent of sulfide oxidation through several mechanisms: fresh sulfide-bearing minerals are continuously brought to the surface and exposed to air; the rock is crushed and ground in the mining and milling processes, thus increasing the surface area of exposed sulfides; and the mine workings themselves may serve as conduits for flow of ground-water and air, thus enhancing the exposure of sulfides still in the ground to oxygenated water. Each of these three activities leads to a slightly different effect on the weathering process. The exposure of fresh (unoxidized) sulfide minerals to air results in an increased mass of sulfide available for oxidation. If left undisturbed in the ground, these sulfides might remain stable until natural processes of uplift or erosion brought them to the surface. Crushing and grinding of rock increases the available reactive surface area, and thus increases the rate at which the sulfides oxidize. For example, the surface area for a given mass of pyrite in the form of cubic crystals increases with the square of decreasing cube dimension, so that the smaller the average crystal size, the greater the surface area available for reaction with oxygen. Because the oxidation rate depends on exposed surface area, the rate increases with decreasing particle size. Lastly, mine workings themselves may become conduits for ground-water flow. Transmissivity of fractures is roughly proportional to the cube of fracture dilation, so more open fractures transmit exponentially greater volumes of water. In this context, mine workings represent almost infinitely transmissive features, especially when compared to the available water supply in most mines. By increasing the rates of ground-water flow, mine workings may increase the rate of delivery of oxygenated water to sulfide minerals still in the ground, thus increasing the rate at which those sulfides oxidize. Conversely, it is possible that the mine workings may speed up the flow rate of ground water to the point that the sulfide oxidation reaction is slow relative to the rate of ground-water flow and smaller masses of sulfides are oxidized. However, in most documented literature cases, the flow from mine tunnels is acidic and metal rich, indicating that the mine workings have the effect of increasing acidity and metal loads to surface-water supplies. Some mine tunnels are specifically designed to lower the local water table and thus to drain mine workings, such as the Reynolds tunnel at Summitville, Colorado, the Argo tunnel at Idaho Springs, Colorado, and numerous other locations. These drainage tunnels are usually driven at the lowest possible elevation to dewater large areas of mine workings. In addition to serving as effective drainage pathways, they speed the delivery of metal loads from the ground water to streams.

The pre-mining condition of the environment depends on the exposure of the deposit to air, as described above. If the deposit is exposed at the surface, the pre-mining condition may include surface waters with low pH and high concentrations of dissolved metals, unfit for most aquatic life other than microbes. Examples of such conditions have been studied in a few places, such as the Red Dog zinc deposit in northwest Alaska (GRAY et al. 1996, KELLEY 1997), Bald Mountain in Maine (SEAL and WANDLESS 1997), Geneva Creek in central Colorado (BASSETT et al. 1992), and Bitter, Iron, and Alum Creeks near Summitville in southwestern Colorado (GRAY and COOLBAUGH 1994, GRAY et al. 1994, KING 1995, MILLER et al. in press), etc. It is perhaps a bit difficult to find such examples today, because many deposits exposed near the surface have already been mined, so it is difficult to establish the pre-mining condition. Useful analogs may be found by examining weakly mineralized altered areas in areas which are geologically and climatically similar to the areas of interest. Also, the proportion of deposits which are actually exposed at the surface may be small. Nevertheless, methods are being developed to estimate the pre-mining concentrations of metals; these will be described later in this paper.

1.2. Natural and manmade contamination of the environment

The quality of surface waters may be poor as a result of the oxidation of sulfide minerals. Numerous case studies (JAMBOR and BLOWES 1994, NELSON et al. 1997) have shown that the primary environmental concerns associated with mineralization, alteration, and mining are the acidity and dissolved or suspended metal loads, and the effect(s) of these additions on aquatic life or potential use of the water resource. Attenuation of the metal loads may occur as a result of dilution or mixing with water of better quality, reaction with country rock or bed material, adsorption or ion exchange, precipitation or coprecipitation, or some combination of these. In most cases, the dissolved metal loads are somehow transferred to the bed load or bed material, through precipitation and settling, or adsorption onto iron oxides that coat the streambed, etc. Thus, the processes that lead to degradation of water quality also may lead to degradation of sediment quality. Sediment quality also may be affected in mined areas by the direct transport of mine-waste material by surface runoff. In many cases, dumps from abandoned mines are in or near active drainages and the dump material may be transported downstream during high stream stages.

When material from a sulfide-bearing deposit is oxidized, the low pH waters that result effectively dissolve many heavy metals. These include: Fe, Mn, Al, Zn, Cu, Cr, Ni, Co, and many of the rare earth elements and actinides. In general, these metals are present in acidic solutions as hydrated cations or weakly hydrolyzed ions. As pH increases, these elements are more strongly hydrolyzed and may precipitate by themselves (esp. Fe, Al, and Mn) as oxyhydroxide solids, or may be adsorbed on the Fe, Al, and Mn oxyhydroxides which precipitate. Metals other than Fe, Al, and Mn are rarely concentrated enough to exceed solubility limits, so adsorption or ion exchange are the most potent attenuation processes for these other elements. Detailed discussions of the mobility of metals in acidic drainages is beyond the scope of this paper, but reviews can be found in JAMBOR (1994), LANGMUIR (1997), NELSON et al. (1997).

2. HOW HAVE WE TRIED TO SOLVE IT IN THE PAST?

2.1. Acid-base accounting

The protocol of acid-base accounting (ABA) was developed, in part, to predict the environmental consequences of developing a mineral deposit. The method is deceptively simple- by conducting a series of analyses of rock samples from a deposit, analyze for minerals which produce acid on weathering (mainly sulfides) and for those which consume acid (mainly carbonates such as calcite; (MORIN 1990). A number of assumptions are implicit in the method. All sulfides are assumed to behave the same as pyrite, effectively, the assumption is made that pyrite is the only sulfide mineral in the sample. Similarly, all acid-neutralizing minerals in the sample are assumed to be equivalent to $CaCO_3$. The ABA method assumes that the total abundance of these minerals is available for reaction, and that no minerals are shielded from the solution either by other mineral grains or by mineral overgrowths. Because this is a total accounting technique, kinetics are ignored. The "static" nature of this test means that it ignores flow rates, water chemistry, and hydrology. Each of these (and other) assumptions limits the degree to which the ABA method describes reality. Therefore, the ABA method, though simple and relatively inexpensive, is severely limited in its application and interpretation. For more information on the ABA method and its limitations, the reader is referred to MORIN (1990) and MILLS (1997).

2.2. Geoenvironmental maps

Environmental impacts of natural mineralized areas and mined areas may be efficiently organized and portrayed within the framework of a Geographic Information System (GIS). In a GIS approach, different layers of in-

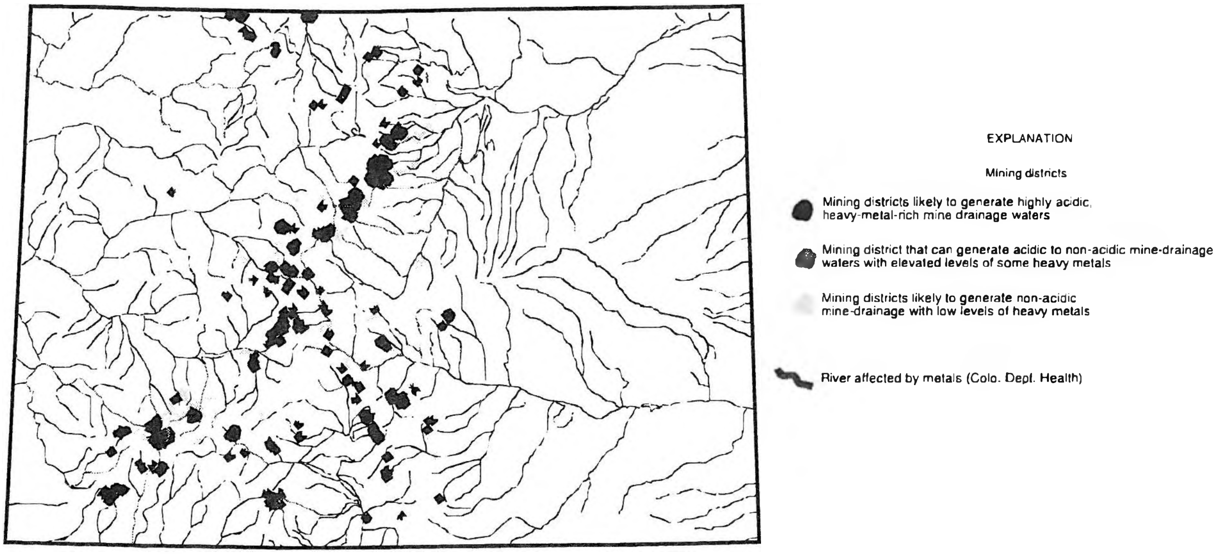

Fig. 1: Map showing potential metal-mine drainage hazards in Colorado, based on mineral-deposit geology (modified from PLUMLEE et al. 1995)

formation can be displayed on a map base, and criteria can be selected for highlighting the display of the data based on specific attributes of the data. Such an approach was taken by PLUMLEE et al. (1995) to evaluate the state of Colorado, USA, for mine-drainage hazard potential (Fig. 1). This geoenvironmental map was the first effort undertaken by USGS to portray a major mineralized region, the Colorado Mineral Belt, in the context of known or expected environmental conditions.

The Colorado map is an highly interpretive product with objective and subjective data layers. Objective data layers include: land ownership (important from the perspective of responsible management of government-owned land); major surface-water divides and drainages; precipitation (for those regions with >50 cm a^{-1}); and locations of major mining districts. The subjective data layers on the map include: drainages which have degraded water quality due to mineralization or mining; and a color-coded portrayal of the major mining districts based on their presumed propensity to cause adverse environmental impacts. This latter ranking derives from an analysis of mineralogic and geochemical investigations of representative ore-deposit types and their known or expected environmental impacts.

The various ore-deposit types were ranked on the basis of the nature and extent of alteration, mineral assemblages, metals present in the assemblage, and the presence of acid-generating minerals like pyrite versus the remnant or natural acid-consuming capacity of the host rocks. In this ranking, deposits which are rich in pyrite and metals and poor in acid-consuming minerals are ranked as most likely to cause environmental problems, pyrite-poor deposits the least. In some ways, this analysis resembles that of the ABA method described above, so there is a need to improve the overall evaluation method. For example, mineral deposits with quartz-alunite and advanced argillic alteration were ranked as most likely to cause deleterious metal impacts because whatever natural acid-neutralizing capacity the host rocks may have had prior to mineralization was consumed by the intensely acidic mineralizing/altering fluids. Thus, during present-day weathering of such deposits, the acid which is generated by sulfide oxidation is not neutralized by reaction with the host rocks. Waters flowing downgradient from such deposits (either in the ground or on the surface) are likely to have extremely low pH (usually <3) and high metals concentrations (usually in the ppm range or greater for metals such as Cu, Zn, As, Cr, Ni, Pb, Co, U and Th). Examples of such deposits in Colorado include Summitville and Red Mountain near Lake City. European deposits in this ranking may include Lahóca, near Recsk, Hungary, and Talagiu, Romania. To effectively remediate the drainage waters from these deposits, the acid must be neutralized and metals removed from the drainage waters. In comparison, drainage waters in contact with carbonate-hosted deposits may be expected to have higher pH's, although concentrations of some metals, especially Zn with minor Pb, Cu, and As, may still be great enough to cause adverse impacts to aquatic life. For these deposits, the greatest remediation concern is to remove the metals dissolved in the water. Examples of this deposit type include parts of the Leadville district, Colorado, and Banska Stiavnica, Slovakia.

The geoenvironmental map of Colorado was an early attempt to classify deposits in a regional and geologic framework. As such, it has the advantage of showing a wide range of deposit types on a single map. This format offers the intuitive ease that comes from assimilating a relatively large amount of information into a spatial, color-coded display. There are also some drawbacks to this approach, which offers the possibility to improve the approach for various applications and end users. For example, the data layers are displayed, but are not queriable. Thus, interpretations can only be derived from the map upon intense inspection and reading of ancillary materials. Because the map is published on paper, it is difficult to add new layers of information, which the user may need in order to customize the map for their particular application. Depending on the specific interests of the end user, it may be desirable to add any of a number of additional data layers to suit a specific need.

The final issue to be raised concerning the Colorado map is that of scale. The map is published at a scale of 1:750,000. This scale is appropriate for the type and specificity of information displayed, and permits display of the map on a conveniently handled piece of paper, approximately 1 meter by 1.2 meter. It is inevitable, however, that the end-users of the map will direct their scrutiny to a specific part of the map and attempt to extract more information than can be reasonably accomplished. The printed map format guards against such abuse because the detailed information is not forthcoming. At the same time, although it leaves the end user with a general regional knowledge and perspective, the lack of specific information may be construed by some as a drawback. The ideal product may be one, which is available in a digital format with scale-appropriate layers of information. More discussion of scale issues will be found in the succeeding section of this paper.

2.3. Geoenvironmental models

Incorporation of environmental considerations into the mineral deposit models was first attempted by the US Geological Survey and summarized in a report by DU BRAY (1995). The format of this effort was designed to be an add-on to the mineral deposit model scheme developed by COX and SINGER (1986) and BLISS (1992). As such, it includes individually authored chapters for major mineral deposit types, cross-referenced to COX and SINGER (1986). Each chapter can be thought of as being an individual geoenvironmental model for the given deposit type. Within the format of this report, major headings exist for overview information for the deposit type, specific geologic and mineralogical factors which influence the environmental behavior of the deposit type, and environmental signatures. Each of these major headings may contain general information about the deposit type, and each may also contain specific information obtained from case studies.

In a published form, DU BRAY (1995) represents the state of the art of geoenvironmental modeling. In particular, the first chapter PLUMLEE and NASH (1995) presents a description of the philosophical approach used in the remainder of the volume and represents what may still be legitimately considered as the state of the art of geoenvironmental modeling. Perhaps the most important observation in PLUMLEE and NASH (1995) is the fact that the environmental effects of ore deposits and mineralized/altered areas extends beyond the boundaries of the alteration because of transport of elements by surface or ground water. Thus, although it would be desirable to develop geoenvironmental models in the same framework as resource models, it may not be practical because the two applications have a different focus and the sphere considered in the resource model is a subset of that considered for the geoenvironmental model. Still, there must be considerable overlap between the two model types because the mineral deposit is the primary source of environmental contaminants in most cases. The altered rock surrounding the mineralized core may be volumetrically important, but in many cases, the concentration of sulfide minerals in the rocks decreases radially outward from the mineralized core so that the altered rocks contain a lesser mass of sulfide than the ore deposit they surround.

Ongoing efforts at the USGS center mainly around refining geoenvironmental models for specific deposits. More work is needed to characterize deposit types in more detail, and to add additional deposit types. For example, placer gold deposits are mentioned only as a highly-eroded extension of low-sulfide Au-quartz vein deposits GOLDFARB et al. (1995). Little or no mention is made of certain deposit types, for example, Ni-laterites. In addition to adding to the environmental databases for specific deposit types, new research at USGS is being directed at watershed-based approaches which may include a number of ore deposits of various types.

While it is important to add to the existing databases, a broader unifying framework is needed within which new deposit environmental models can be developed, and which can be used to conduct environmental assessments of regions containing one or more deposit types. The remainder of this paper is devoted to descriptions of various existing methods by which environmental impacts can be anticipated, and to descriptions of other physical and chemical properties of mineral deposits and the environments in which they occur, which may contribute to the formulation of geoenvironmental models.

3. USES FOR GEOENVIRONMENTAL MODELS

Once a framework for geoenvironmental models is established, their potential uses and applications are numerous. They fall under two categories: as a framework for environmental or ecosystem classification; and as an evaluation tool for mineral deposits and altered areas and the expected environmental impact of these areas, whether mined or not. The framework for ecosystem classification may be established by observing that the rocks, soils and water in an ecosystem comprise the substrate for all biological activity. Thus, a detailed understanding of the geologic and hydrologic properties of an ecosystem is a logical first step towards understanding the ecosystem as a whole. As an evaluation tool for the environmental impacts of mineral deposits, geoenvironmental models should characterize the nature and extent of acid generation versus consumption, and mobilities of certain metals and other elements.

Geoenvironmental models have applications to the "life-cycle" treatment of mineral deposits. The life-cycle concept examines all aspects of a mineral deposit from the time of its formation through the post-mining reclamation. Because each step in the life cycle is fundamentally a geologic or hydrologic process, the geoenvironmental models should be able to address expected or known environmental issues associated with each step in the life cycle as well. As a subset of the life-cycle, the geoenvironmental models may be one component of a pre-mining economic analysis for an as yet undeveloped deposit.

Other issues specifically related to mining may be addressed by the geoenvironmental models. These include: determination of pre-mining background concentrations of acidity and metals in mined and unmined areas; anticipating the environmental impacts of new mining developments prior to mining; and resolving the relative contributions of different deposit types in a watershed to the overall loads of metals and acidity. These issues are of keen interest to regulatory authorities who must decide whether a mine has caused environmental impacts which exceed those caused by natural weathering and erosion processes. Therefore, in addition to qualitative descriptions of mineral deposits and altered areas, the geoenvironmental models should contain quantitative information which may relate to acid and metal loads in the environment.

4. NEW DIRECTIONS

Having developed the existing framework of environmental models and their uses, the remainder of this paper is devoted to describing some types of information that may be included in geoenvironmental models, as well as some proposed approaches to geoenvironmental modeling in a regional context. The data layers required and the approach taken to formulating the models must be sufficient to address the intended uses, and for the sake of completeness, the format in which the models are presented should be able to accommodate new data layers, which the end user may see fit to add. Depending on the application, these additional data layers may address climatic and biological effects, scale-dependent phenomena such as mineralogic and geologic variability, and other physical and chemical properties of mineralized rocks.

New research at USGS is aimed at developing a unifying framework for geoenvironmental models. At this writing, the concept which seems to offer the most promise is to describe the environmental characteristics of mineralized areas in the context of ecoregions. Ecoregions, broadly defined, are geographic divisions of land masses which are distinguished from one another on the basis of landform, climate, soils, vegetation, and other characteristics. BAILEY (1995) presents a thorough description of ecoregions for the United States, based on the original ecoregion concept proposed by KÖPPEN (1931). The same physical characteristics which cause a region to lie within a particular ecoregion also affect the environmental behavior of mineralized areas, and so may represent a useful scheme by which environmental impacts of mineralized areas can be classified. The ecoregion map for the conterminous US (excluding Hawaii and Alaska) is shown in Fig. 2. The domains shown on the map represent the broadest level of classification of ecoregions. On the original map BAILEY (1995), there are numerous divisions within each domain, based strongly on latitude and its attendant climatic effects. On Fig. 2, stippled regions represent generally warmer, wetter climates with well-developed soils and vegetation. Striped areas represent mountainous regions with climates, soils, and vegetation, which vary greatly with altitude. Areas with gray shading represent generally drier climates with less extensive soil development and decreased density of vegetation.

Undoubtedly there will be a dramatic difference in the environmental behavior of a mineralized area in one ecoregion from another. For all the factors mentioned above–temperature, moisture, biological productivity, etc.–there is an attendant effect on the rate and extent of sulfide weathering which in turn dictates the environmental signature of a mineralized area. This concept is the basis for new research at USGS and several projects

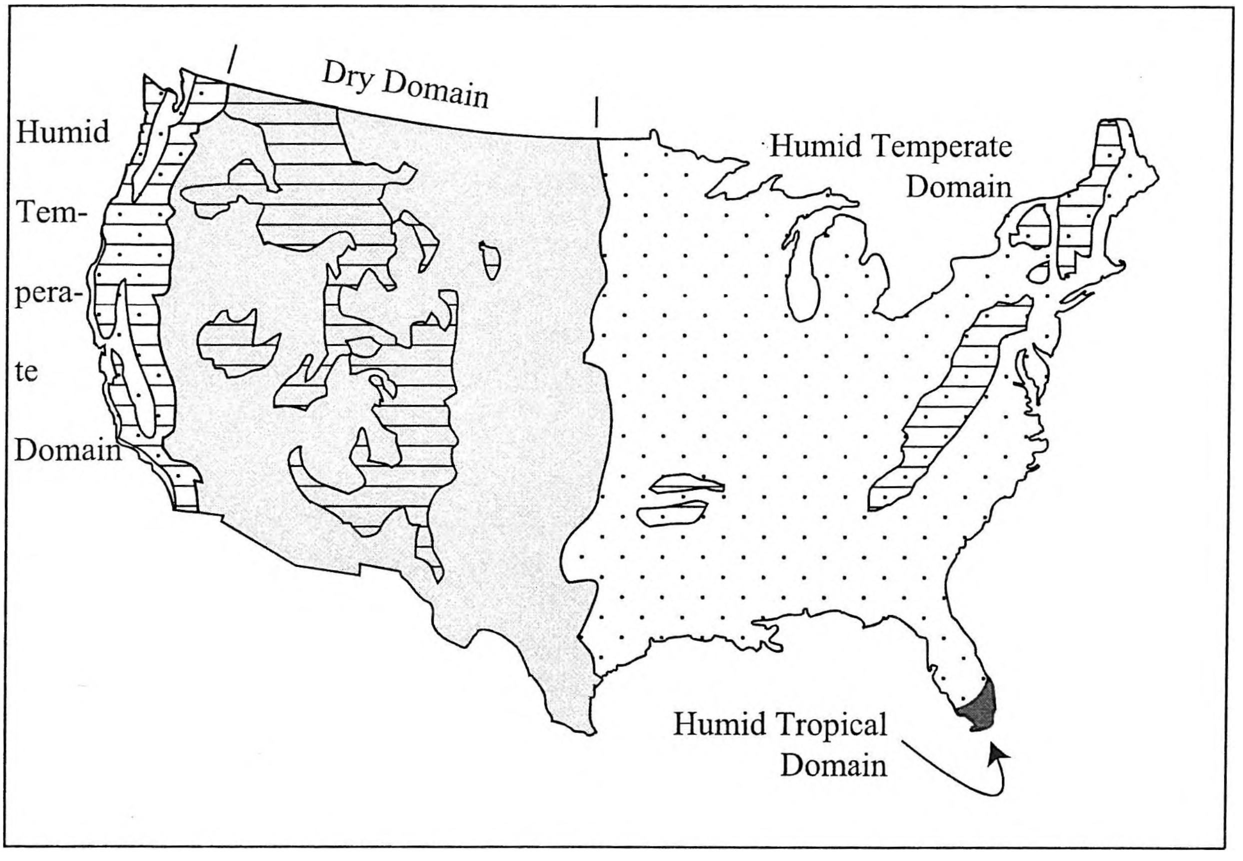

Fig. 2: Map of the conterminous United States showing major ecoregion domains (modified from BAILEY 1995)

are examining the comparative environmental signatures of geologically similar mineral deposits in different climatic or ecoregional settings. The results of this research should help refine many of the concepts discussed in this paper.

It is possible that the combined ecosystem/watershed approach to understanding water/rock interactions will have applications to other environmental problems, such as understanding regional geochemistry and baselines, evaluating ecosystem conditions within regions subject to dramatic fluxes of human population or to changing climate, etc. Full discussion of these topics is beyond the scope of this paper, but more information can be obtained in HUGGETT (1995), BAILEY (1998), and SHUGART (1998)

5. HOW ARE THESE MODELS GENERATED?

Given the rather broad scope of geoenvironmental models, some fundamental questions remain:

- What types of data should be gathered in field investigations?
- How will the models be constructed?
- Who are the primary end users of these models, and what data layers are most critical for their uses?
- How will the models be presented or published; on paper, electronic media, etc.?

These four questions lead to a fundamental question which geoscientists must now answer, namely: How should a research program be designed to gather all the data and interpretations necessary to construct a geoenvironmental model? At this writing, the question remains unanswered, largely because the market of end users has not been developed. Therefore, an evolutionary period has now begun within which geoenvironmental models will continue to change as new uses and applications are discovered by land-use managers and planners, environmental regulators, the public, etc. In this volume, ÓDOR et al. (1999) present a geoenvironmental assessment for northeastern Hungary which is based on a regional sampling of sediments in floodplain and overbank deposits. These samples were collected from near-surface (0-10 cm depth) and deeper (50-60 cm depth) horizons, and are thought to represent the present and the pre-anthropogenic conditions. Based on statistical analyses of the sediment chemistry, anomalies are plotted as ranked scores on a base map of the area under investigation. This relatively new approach demonstrates the potentially widespread environmental effects associated with mineralized or mined areas. It has the advantage of showing a relatively small region (tens of thousands of square kilometers) in great detail through a rigorous sampling program. Because of the great sample density, it is possible to resolve the environmental signatures of individual mines or districts on the maps presented by ÓDOR et al. (1999). On the other hand, many of the long-range framework items discussed in this report (ecoregion, climate, etc.) cannot be addressed by ÓDOR et al. (1999) because the area they studied does not have great climatic or ecoregion variability. Thus scale dependence is seen once again as an fundamental parameter in geoenvironmental models.

6. CONCLUSIONS

Development of geoenvironmental models represents a new direction in the environmental geosciences as it incorporates regional syntheses of climatic and ecological variables with a geologic and geochemical framework to describe environmental signatures associated with mineralized and altered areas. Uses of geoenvironmental models include land-use management and planning, and environmental regulation. Properly and completely constructed, these models should aid land-management decisions such as whether a region would be expected to be severely impacted by new mine development, whether observed high metal loads in an area can be attributed to natural or anthropogenic processes, and the regional environmental impact attributable to mineralization, alteration, or mining. The art of the geoenvironmental model is relatively young and a great degree of evolutionary development is to be expected. The forces driving and guiding this evolution include technological developments and end-user applications. The former will control the amount of information which can be reasonably presented in a single package and the mode of presentation; the latter will control the content of the models. As the end-user market is more fully developed, the desired or required content will likely change, and it is expected that geoenvironmental models will not follow a standard template. That is, depending on specific local or regional issues, the various data layers which may be incorporated into the geoenvironmental models are expected to change in priority.

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