APPLICATIONS OF A GLOBAL MINERAL-RESOURCE ASSESSMENT FOR ADDRESSING ISSUES OF SUSTAINABLE MINERAL RESOURCE DEVELOPMENT[1]

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Abstract. The future of mining depends on balancing global demands for minerals with societal demands for sustainable development. The U.S. Geological Survey, in collaboration with a variety of international cooperators, is assessing the undiscovered global resources of copper, platinum-group elements, and potash at a scale of 1:1,000,000. Assessment products include maps that show significant identified deposits and permissive areas for undiscovered deposits, as well as probabilistic estimates of contained metal. Derivative products applicable to sustainability issues include maps showing the spatial relationship of permissive areas to infrastructure development, protected areas, threatened ecosystems, seismically active areas, and watersheds.

Additional Key Words: assessment, mineral resources, sustainability

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Introduction

The future of mining depends on balancing global demands for minerals with societal demands for sustainable development. Mining benefits society by meeting global demands for nonfuel mineral commodities, stimulating economic growth, and possibly reducing poverty in developing countries. Concomitantly, mining poses risks to ecosystems and human health, and affects land use. Societal concerns about population growth and the effect of human activities on the natural environment led the U.N. World Commission on Environment and Development to define the goal of sustainable development in 1987 as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." The view of mineral development as a threat to protected areas and biodiversity is recognized as one of the many issues that has plagued the mining industry in the past. The mining industry formally addressed the role of mining in sustainable development starting in 2000 through a two-year project on Mining, Minerals, and Sustainable Development (MMSD). The final report for that project, "Breaking New Ground", identified sustainable development principles and challenges, identified key actions and responsibilities, and defined a vision for a sustainable future for the mining and minerals sector (International Institute for Environment and Development (IIED), 2002).

Global demand for nonfuel mineral resources will continue to increase in the foreseeable future due to global population growth and efforts to improve standards of living. No global shortages of nonfuel mineral resources are expected in the near-future; however, global patterns of mineral consumption are likely to change. The world mine production for Cu increased by 6.6% in 2004 (U.S. Geological Survey, 2005). Copper production remained constant or increased between 2003 and 2004 for all countries except Indonesia where a landslide in 2004 reduced production from a major mine (Fig. 1). Menzie and others (2003) examined relationships among population, Gross Domestic Product, and selected mineral consumption for the twenty most populous countries for the period 1970 through 1995. Some developing countries had rapid growth in consumption of commodities such as Cu relative to the stable patterns of consumption observed for many developed countries. The analysis suggested that if China reaches the level of Cu consumption of developed countries, world consumption of Cu could double relative to 1995 global Cu consumption. To meet the growing demand for minerals requires not only increased production from known deposits, but continued exploration for, and development of, new mineral deposits.

The focus of much of the world's nonfuel mineral exploration and development has shifted from developed nations to relatively unexplored and undeveloped nations in Latin America, Asia, and Africa. Worldwide expenditure on nonferrous mineral exploration increased from the early 1990's through 1997, fell between 1997 and 2002, and rebounded in 2003 and 2004, with expectations for continued increases in 2005; most of the exploration dollars were spent in Latin America, Canada, Africa, and Australia (Metals Economics Group, 2004). Many areas that are currently attractive for mineral exploration also are areas of high ecological value, stressed watersheds, socially vulnerable communities, or natural hazards (Miranda et al., 2003; Sweeting and Clark, 2000).

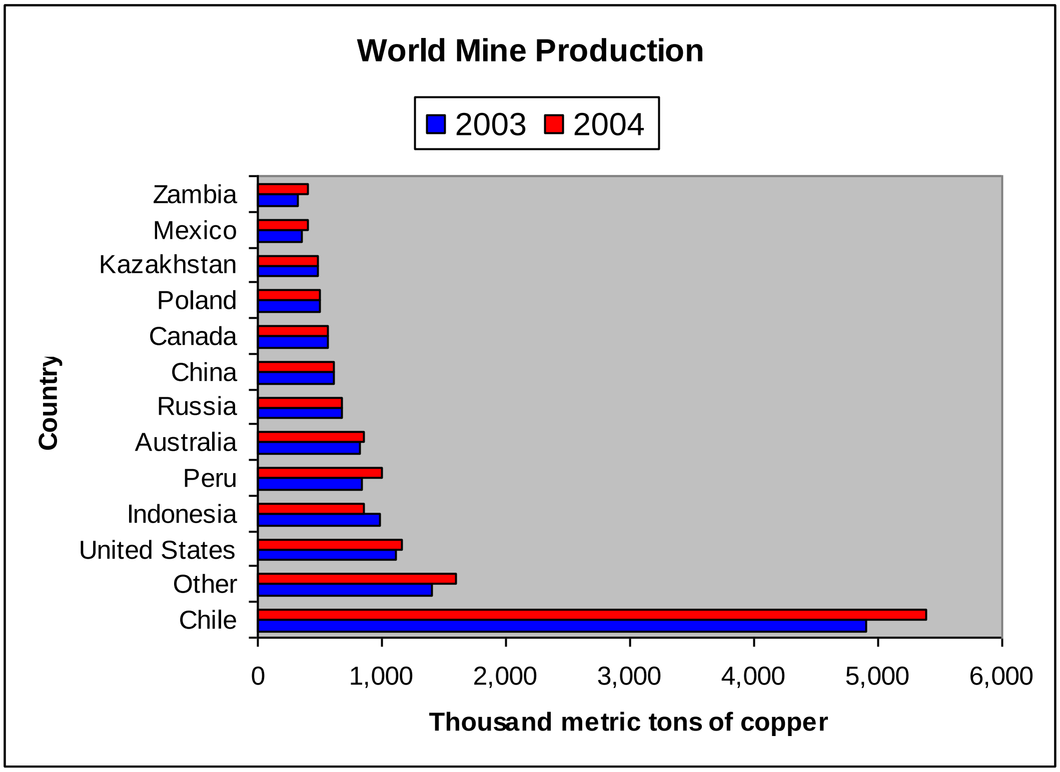

Figure 1. World mine production for Cu for 2003 and 2004 (U.S. Geological Survey, 2005).

Informed planning and decisions about sustainable resource development require a long-term global perspective and an integrated approach to resource, environmental, and land-use management. Such an integrated approach to sustainable resource development requires unbiased information on the global distribution of identified and undiscovered mineral resources, the economic factors influencing their development, and the environmental consequences of their exploitation. Knowledge of areas where mining "could go" is fundamental to establishing informed policies on where mining "should go" as well as "not go". In response to the growing need for global mineral resource information, the U.S. Geological Survey (USGS) is conducting a Global Mineral Resource Assessment Project (GMRAP) to assess the world's undiscovered nonfuel mineral resources (Briskey and others, 2001; Briskey and Schulz, 2002; Schulz and Nokelberg, 2004). The goals of the project are to outline the principal land areas in the world that have potential for selected undiscovered non-fuel mineral resources and to estimate the probable amounts of those mineral resources to a depth of one kilometer below the Earth's surface. A variety of global environmental databases and spatial datasets currently exist for environmental assessment (for example, Singh and others, 1997; Tateishi and Hastings, 2000; WDPA Consortium, 2005). The maps produced by GMRAP provide information on the principal areas in the world where undiscovered deposits of selected mineral commodities in selected types of mineral deposits are predicted to occur. In this paper, we describe the global mineral resource assessment, provide examples of products, and explore some applications of the assessment.

The Global Mineral Resource Assessment

Overview

The global mineral resource assessment is an eight-year cooperative, international project that started in 2002. Eight commodities are included in the assessment, which is being conducted in phases for seven regions of the world (Fig. 2). The first phase addresses global mineral resources for Cu, Pt-group elements, and potash. Subsequent phases of the assessment will include Au, Pb, Zn, Ni, and phosphate. Copper was selected because it is globally distributed and is important for electrical and other industrial applications. For each commodity, only the most significant deposit types for world mineral supply are considered in the assessment. For example, most (~80%) of the world's Cu comes from porphyry Cu and sediment-hosted Cu deposits. Therefore, the assessment for Cu is restricted to porphyry Cu and sediment-hosted deposits although smaller undiscovered resources of Cu are present in other deposit types. Platinum-group elements were chosen because they have critical applications as catalysts in a number of industries, supply is limited and extraction is expensive, and only a few deposits are known globally. Potash was chosen because it is an essential fertilizer in food production.

The USGS has developed a quantitative form of resource assessment that allows explicit expressions of the degree of uncertainty associated with assessments and allows economic analysis (Singer, 1993). By using a quantitative form of assessment, geology-based results can be translated into a format usable in decision-support systems, cost-benefit analyses, and/or evaluation of the consequences of alternative resource-related decisions (i.e., money). The assessment is conducted by regional assessment teams of scientists from the USGS, international cooperators, and other regional experts and economic geologists (Peters and Back, 2003; Doebrich et al., 2003; Schulz and Briskey, 2003; Schulz et al., 2004). Teams compile existing geologic data for regions and conduct the assessment at a scale of 1:1,000,000. The USGS previously conducted a quantitative assessment of undiscovered deposits of Au, Ag, Cu, Pb and Zn in the United States, hereafter referred to as the U.S. National Assessment (Schruben, 2002). Results of that assessment will be incorporated into the global assessment for North America (Fig. 2). Examples of applications of a global mineral resources assessment included in this paper are based on published data for the United States and published global data sets.

Form of Assessment

The three-part form of assessment described by Singer (1993) was adopted for the global assessment. In this form of assessment, mineral deposit models are used to link deposit types with geologic environments. A mineral deposit is defined as a mineral occurrence of sufficient size and grade that it might, under the most favorable circumstances, be considered to have economic potential. A mineral deposit model is defined as a systematic arrangement of information that describes the essential attributes of a class of mineral deposits (Cox et al., 1986). For the purpose of this study, a complete model includes descriptive information on geologic characteristics of the class of mineral deposit as well as global grade and tonnage data that characterize the quantitative aspects of an economic to sub-economic subset of thoroughly studied deposits belonging to the class. The descriptive model describes the geologic environment in which the deposits are found, such as host rock type, tectonic setting, and depositional environment, as well as the identifying characteristics of the class of deposit such as mineralogy, alteration, and ore controls.

The three parts of the assessment are as follows:

1. Areas (mineral resource tracts) permissive for the occurrence of undiscovered mineral deposits of a particular type are delineated according to the geology,
2. Numbers of undiscovered deposits of each type are estimated, and
3. Quantities of resources contained in the undiscovered deposits are estimated using grade and tonnage models.

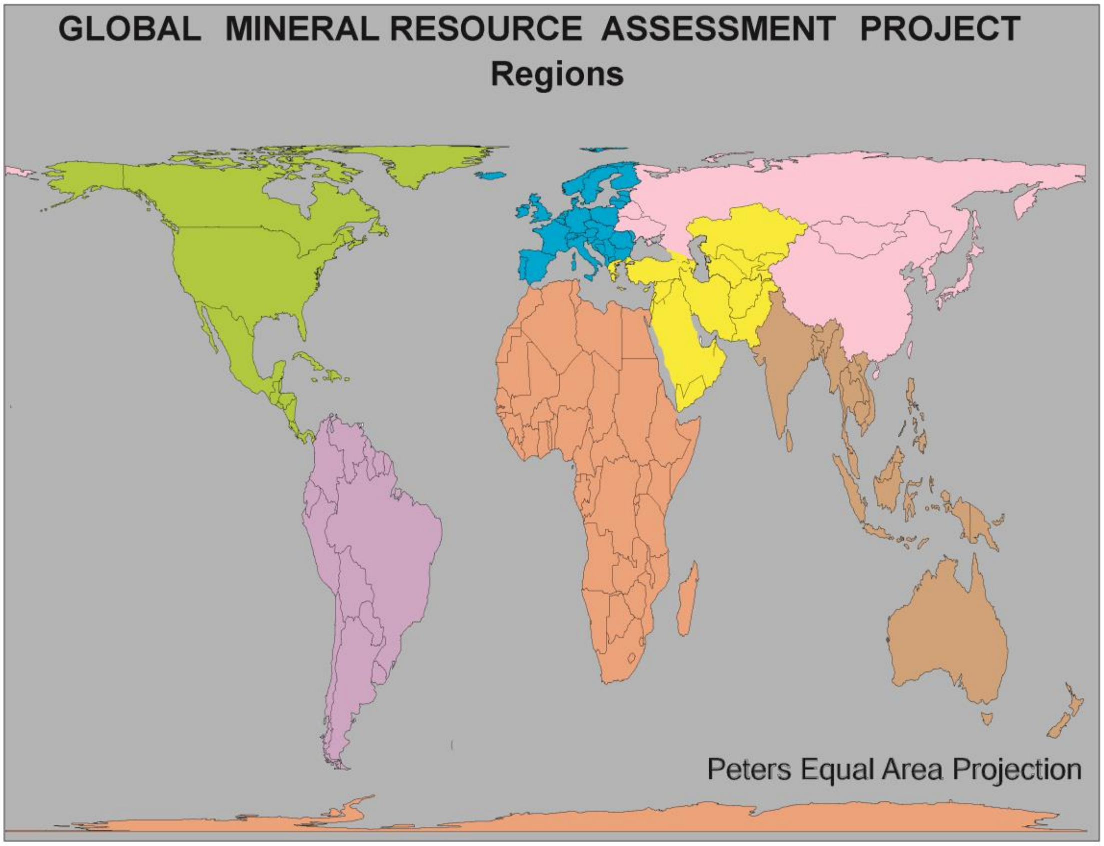

Figure 2. The seven assessment regions for the global mineral resource assessment.

Data needed to choose appropriate mineral-deposit models and construct mineral resource tract maps include geologic maps, databases of known mineral deposits and occurrences, exploration history and, if available, ancillary data such as geochemical or geophysical data (Fig. 3). Numbers of undiscovered deposits are estimated by subjective probabilities based on expert consensus, by statistical guides using mineral deposit densities for analogous areas (Singer et al. 2001, 2005a; Singer and Menzie, 2005), or by other means. Quantities of resources are calculated by combining probabilistic estimates of numbers of undiscovered deposits with grade and tonnage models for the deposit type in a Monte Carlo computer simulation (Root et al., 1992; Duval, 2000). Assessment results can be evaluated by using economic filters (Duval, 2004), cash-flow models, and other tools for economic, environmental, and policy analysis. Figure 4 illustrates the three-part form of assessment and applications of potential mineral supply, environmental planning, land-use planning, and economic planning. The three-part form of mineral resource assessment is internally consistent because the mineral resource tracts are delineated on the basis of the descriptive mineral-deposit model, the grade and tonnage models are consistent with the descriptive models and with known deposits in the area, and the estimates of number of undiscovered deposits are consistent with the grade and tonnage model (Singer, 1993).

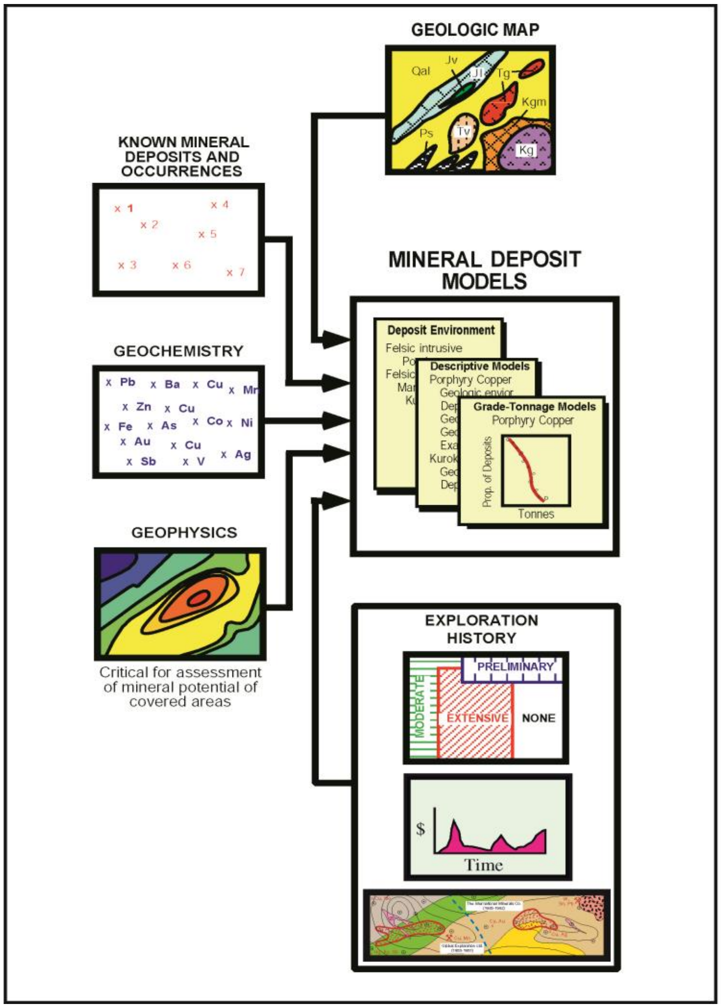

Figure 3. Data inputs for a three-part form of quantitative mineral resource assessment.

<u>Assessment products</u>

The results of the global assessment will be published by the USGS by regions, in conjunction with international cooperators. Products will include:

- Mineral resource tract maps
- Rationales for selecting the mineral deposit model, delineating tracts, and making numerical estimates of numbers of undiscovered deposits
- Tables showing the probabilistic estimates of numbers of undiscovered deposits and the estimated amounts of contained metal and mineralized rock
- Histograms and cumulative distribution graphs of estimated metal and mineralized rock

- Mineral deposit model information and lists of significant known deposits

Data for porphyry-Cu deposits from the U.S. National Assessment (Schruben, 2002) are used to illustrate assessment products. Figure 5 shows some of the mineral resource tracts for porphyry Cu deposits in the conterminous United States. Tract PC05 for example, outlines an area of 45,100 km^2 in the Pacific Coast region of Oregon and southern Washington. The tract includes outcrops of mapped Tertiary volcanic rocks of the western Cascades as well as concealed magnetic plutons interpreted from geophysical data. In the rationale for tract PC05,

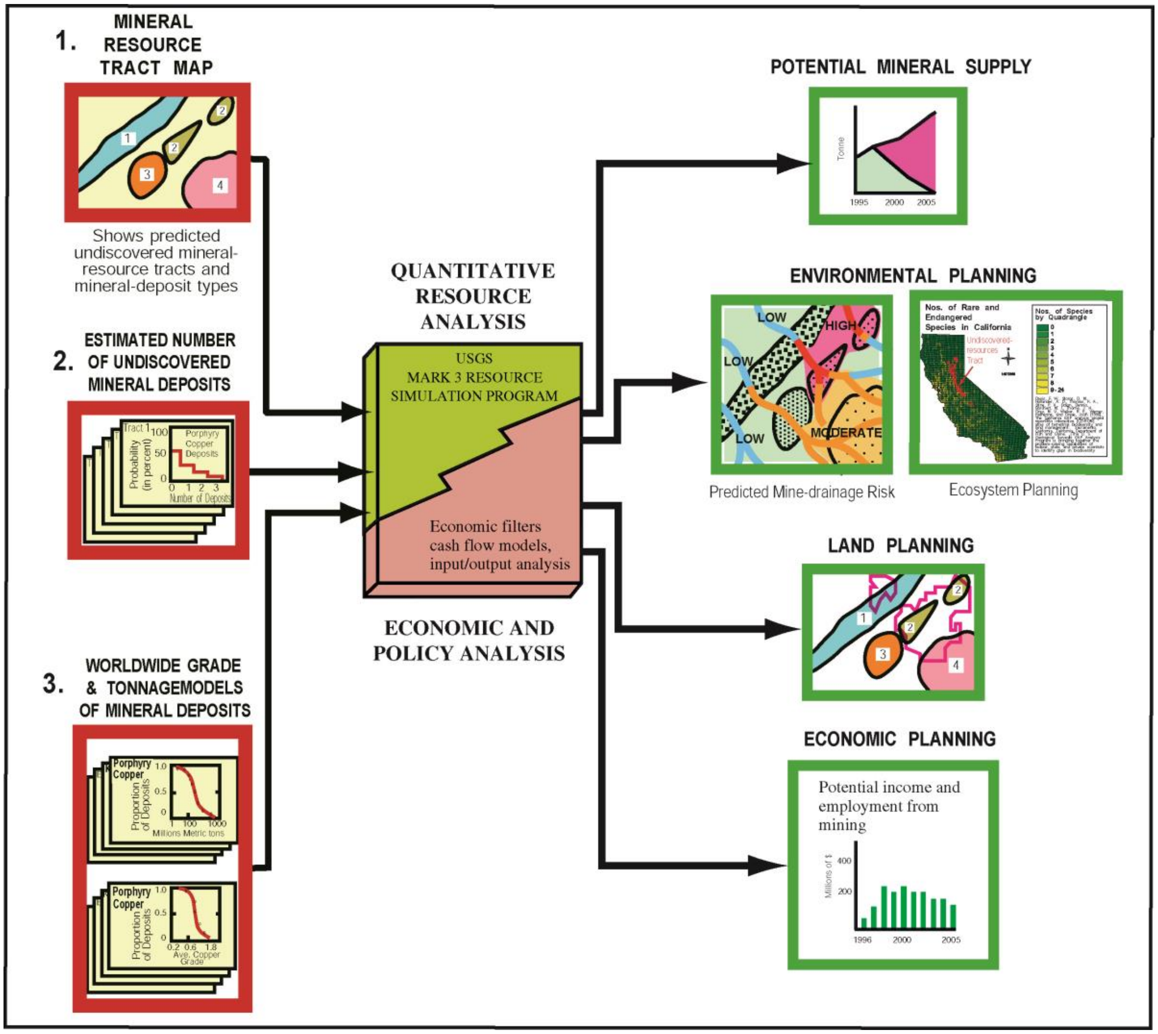

Figure 4. The three-part form of assessment (Singer, 1993) includes (1) delineation of areas permissive for undiscovered resources, (2) estimation of number of undiscovered deposits, and (3) estimation of the amount of resources they contain. The quantitative assessment allows the geology-based results to be translated into a format usable in decision making for mineral supply, environmental, land, and economic planning.

Ashley (in Schruben, 2002) noted that undiscovered porphyry Cu deposits in the southern Cascades are expected to have grade and tonnage characteristics similar to porphyry Cu deposits in British Columbia and Alaska (Menzie and Singer, 1993). Tract PC05 contains one known porphyry Cu deposit, the Margaret deposit of southwestern Washington. The assessment team concluded that further exploration of known prospects in tract PC05 could identify additional deposits. The rationale also includes a discussion of details of tract delineation, provides references to geologic maps and reports for the area, describes known deposits and prospects, and explains the reasoning behind the numerical estimate of numbers of undiscovered deposits. The assessment table (Table 1) includes the subjective estimate of numbers of undiscovered deposits for Tract PC05, as well as the output from the computer simulation based on the appropriate grade and tonnage model.

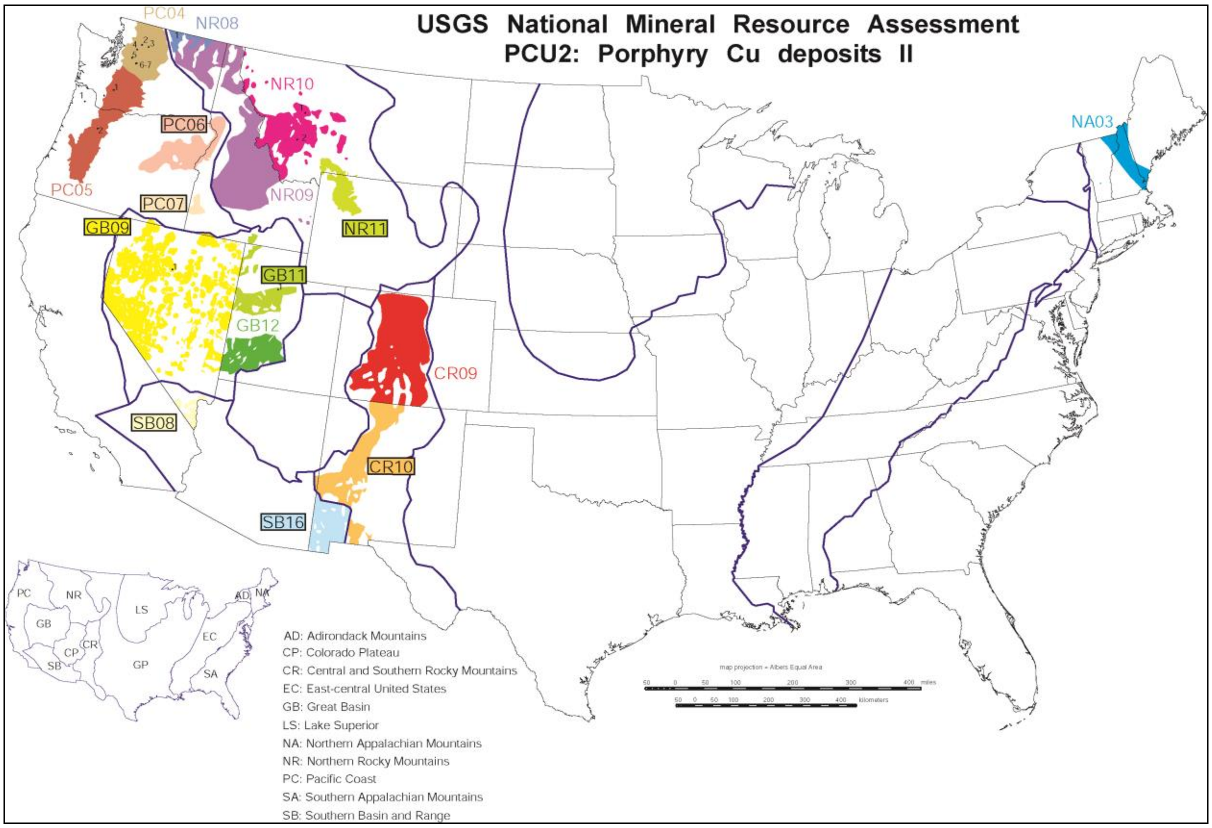

Figure 5. Mineral resource tract map showing some of the permissive tracts of porphyry Cu deposits in the conterminous United States. Heavy lines separate regions defined for the national assessment. Map from Schruben (2002).

Applications

Sustainable development

Assessments of undiscovered mineral resources provide a basis to help society recognize, discuss, manage, and minimize environmental impacts associated with mineral exploration and mining while maintaining or expanding mineral supplies. Quantitative assessments are essential for effective evaluation of the consequences of alternative resource-related decisions. Potential applications of the global assessment include mineral supply issues, evaluations of tradeoffs associated with mineral development, and environmental planning. Mineral resource tract maps can be combined with other types of data at appropriate scales. For example, mineral resource tracts permissive for the occurrence of undiscovered porphyry-Cu deposits in the United States are plotted on a map of the western hemisphere in Fig. 6, along with known porphyry-Cu deposits from a global database (Singer et al., 2005b) and the distribution of biodiversity “hotspots” from a global database. Biodiversity “hotspots” are defined by Conservation International as regions that contain at least 1,500 endemic species of vascular plants and that have lost at least 70 percent of their original habitat (Myers, 1988; Myers et al., 2000; Mittermeier et al., 2004). The map shows that known porphyry Cu deposits overlap hotspots in some database (Singer et al., 2005b) parts of the world such as western South America, but not in others. The completed global assessment for Cu will show tracts for other countries that will include areas that are geologically permissive for the occurrence of undiscovered porphyry-Cu deposits. Such maps can be used to anticipate areas where mining might have relatively low or high impacts on biodiversity. Similarly, mineral resource tracts can be compared with other spatial data such as population densities, poverty maps, water resource maps, agricultural areas, or other human or ecological indices of the state and wellbeing (Prescott-Allen, 2001) of a particular area as a planning tool for considering mineral resources and their extraction in a sustainable development framework.

Table 1. Quantitative estimate of undiscovered resources in Tract PC05. Estimates of numbers of undiscovered deposits were made subjectively by an expert panel. These estimates were combined with grade and tonnage models and an economic filter by a program named EMINERS (Duval, 2004), which uses a Monte Carlo simulation described by Root et al. (1992) to estimate mineral resources and their net present value.

The tract ID is **PC05**

The EMINERS Index is 68: BC/AK Porphry Cu(17.1)

There is a 90% or greater chance of 1 or more deposits.
There is a 50% or greater chance of 3 or more deposits.
There is a 10% or greater chance of 10 or more deposits
There is a 5% or greater chance of 10 or more deposits.
There is a 1% or greater chance of 10 or more deposits. Mean Number of Deposits = 4.4

Estimated amounts of contained metal and mineralized rock (metric tons)

quantile	Cu	Mo	Au	Ag	Rock	Present Value
0.95	0	0	0	0	0	$0
0.90	110,000	0	0	0	28,000,000	$0
0.50	2,100,000	53,000	84	540	630,000,000	$260,000,000
0.10	6,900,000	290,000	405	3,000	2,100,000,000	$1,300,000,000
0.05	8,500,000	400,000	550	4,200	2,500,000,000	$1,700,000,000
mean	3,000,000	110,000	150	1,100	870,000,000	$480,000,000
Probability of mean	0.40	0.33	0.37	0.35	0.40	0.36
Probability of zero	0.07	0.15	0.17	0.23	0.07	0.33

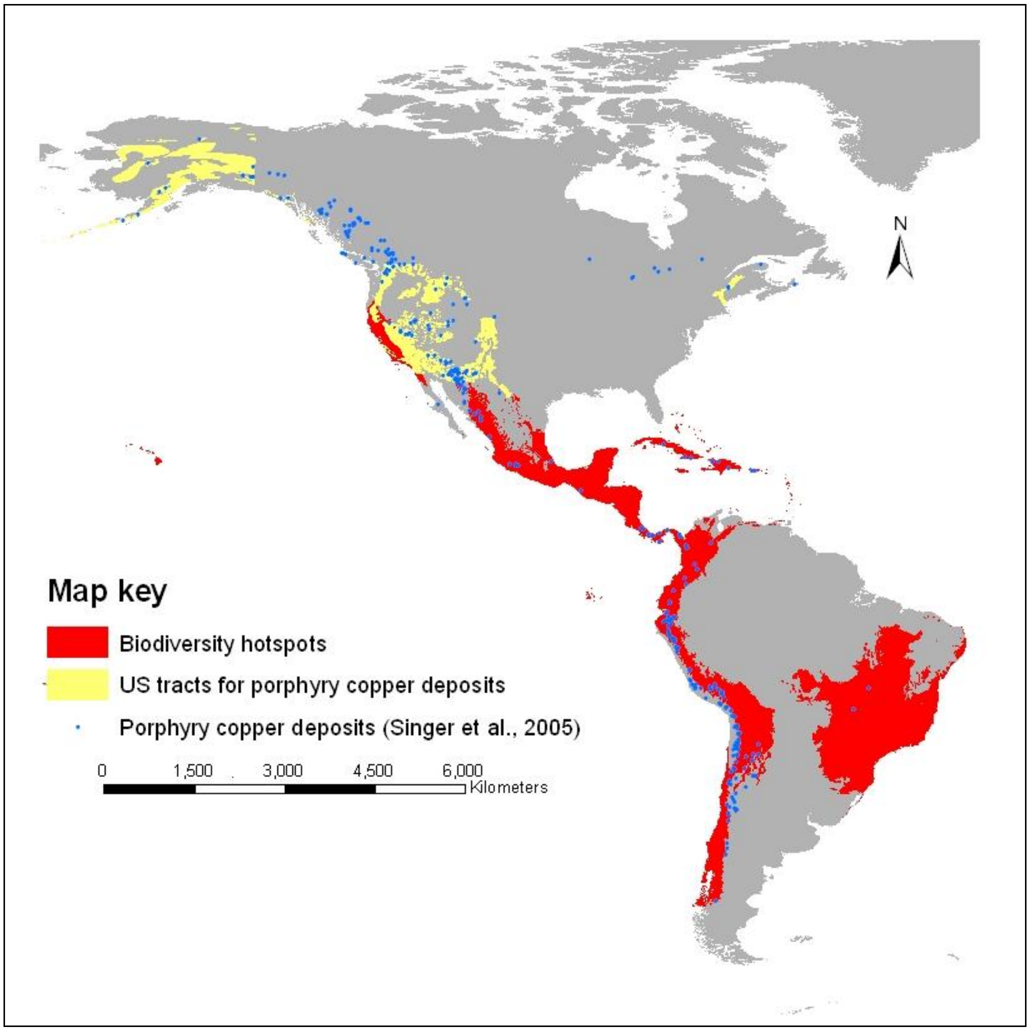

Figure 6. Western hemisphere map showing global biodiversity "hotspots" defined by Conservation International, global known porphyry Cu deposits (Singer et al., 2005b), and mineral resource tracts for undiscovered porphyry-Cu deposits in the United States (Schruben, 2002).

<u>Resource potential</u>

The U.S. National Assessment estimated the amount of Cu in undiscovered mineral deposits in the United States as ranging from 170,000 kilotonnes (kt) at a 90-percent probability to 440,000 kt at a 10-percent probability, with a mean estimate of 290,000 kt with 69 percent of the Cu contained in undiscovered porphyry Cu deposits (U.S. Geological Survey National Mineral Resource Assessment Team, 1998). The mineral resource tracts for undiscovered porphyry Cu deposits in the U.S. are plotted in Fig. 7, where they are classified by mean estimated Cu. This type of map shows that, although large areas in Alaska and western states are permissive for the occurrence of porphyry Cu deposits, the assessment predicts that the most prospective area for undiscovered porphyry Cu deposits is in the southwest (red field, Fig. 7).

Land use and natural hazards

Many areas of the world are withdrawn from mining by international or national proclamation. Sources of future mineral supply are becoming more restricted as mineral development is prohibited, or proposed to become prohibited, in protected areas and as numbers of protected areas increase. National protected areas such as parks, natural monuments, and habitat/species management areas are categorized by the World Conservation Union (IUCN) by management objectives, such as recreation, ecosystem protection, science, or conservation of natural features. Mining is banned in some nationally designated protected areas. Internationally recognized protected areas include World Heritage sites of outstanding natural and cultural value, Ramsar Convention wetlands of international importance, and UNESCO designated Biosphere Reserves. The issue of mining within and near such sites is controversial. Threats that mining poses to such areas are debated and unresolved (Phillips, 2001).

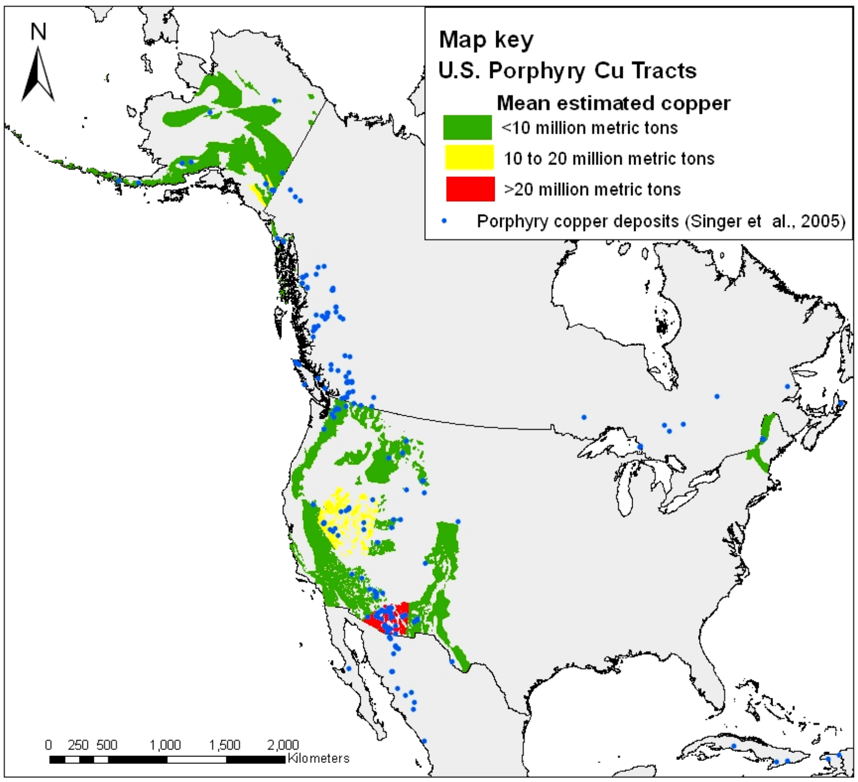

Figure 7. Mineral resource tracts for undiscovered porphyry Cu deposits in the United States classified by mean estimated Cu (Schruben, 2002). Individual tract boundaries are omitted for clarity. Known porphyry Cu deposits from Singer et al. (2005b).

In the global assessment, mineral resource tracts are based on geological, not political, considerations. Thus tracts may include or overlap protected areas. Figure 8 is an example of how a mineral resource tract could be combined with other types of data for planning purposes. Mineral-resource tract PC05, which was used in the example of quantitative assessment products (Table 1) overlaps parts of several terrestrial ecoregions in the Pacific northwest defined by the World Wildlife Fund (Olson and Dinerstein, 1998). The tract encompasses a number of volcanoes, including the recently active Mount St. Helens, and loci of earthquakes having magnitudes >4 (Hearn et al, 2000). The tract includes one known porphyry Cu deposit, the Margaret deposit discovered in 1971 in the St. Helens mining district north of the volcano (Fig. 8a). There was exploration for base and precious metals in the St. Helens mining district from 1892 until the 1980 volcanic eruption (Moen, 1977). Severe forest fires affected mining operations in the Cascades intermittently during that time period. The 30-year prediction of future conservation status by the World Wildlife Fund, given current conservation status and trajectories, ranks the Central and Southern Cascades Forests ecoregion as vulnerable, whereas the other ecoregions in tract PC05 are classified as critical or endangered. Note that some mineral resource tracts north and south of PC05 include more known porphyry Cu deposits and relatively stable or intact ecoregions (Fig. 8a). Most of Tract PC05 is in National Forest lands, which are open to mining subject to approval by the USDA Forest Service (Fig. 8b). The tract also includes Mount Ranier National Park, and borders Crater Lake National Park. Mining is prohibited in National Parks in the United States. The eastern boundary of the tract intersects a protected area of international importance, the Three Sisters Wilderness, which is a designated UNESCO-MAB Biosphere Reserve. In 2005, a mining company applied for a lease to conduct exploratory drilling for Cu in the National Forest north of Mount St. Helens, noting that mining in the area could boost a local economy depressed by jobs lost in the timber industry (The Olympian, 2005). A nonprofit group has opposed the exploration project on environmental grounds (The Gifford Pinchot Task Force, 2005). This example highlights the challenges of mineral resource development in a sustainable development context and the need for unbiased minerals information for land-use decisions. Regional- and global- scale analysis of the distribution of potential areas of mineral supply relative to each other, and relative to measures of other natural resource and human resources, provides a tool for long-term planning and decisionmaking. Habitat disturbance and fragmentation are leading causes of species extinction. Recent trends in global Cu demand and rising Cu prices may stimulate mining industry interest in areas that formerly were less attractive for exploration and development. As lands available for mining decrease, global assessment information will become increasingly important for identification and analysis of remaining alternate sources of future mineral supply. Without such information, options for future mineral supply could be unknowingly foreclosed. With such information, future mining may be planned and conducted to result in reduced environmental degradation, improved economic benefits, and enhanced social values (Briskey et al., 2002).

Potential environmental impacts

The recognition of the environmental impacts of mining has increased societal concern about ecological- and human-health threats associated with historic and modern mining. Many of the geologic characteristics summarized by a mineral deposit model determine the environmental signature of the deposit. The mineralogy and host rock for a particular deposit type, for example, provide information on the potential of ore and waste rock to generate or neutralize acidity. Environmental effects generated by deposit geology are modified by geochemical and biogeochemical processes within and external to the deposit, anthropogenic factors such as mining and mineral processing methods, and climate (Plumlee and Nash, 1995; Wanty et al., 1999; Berger and Drew, 2002).

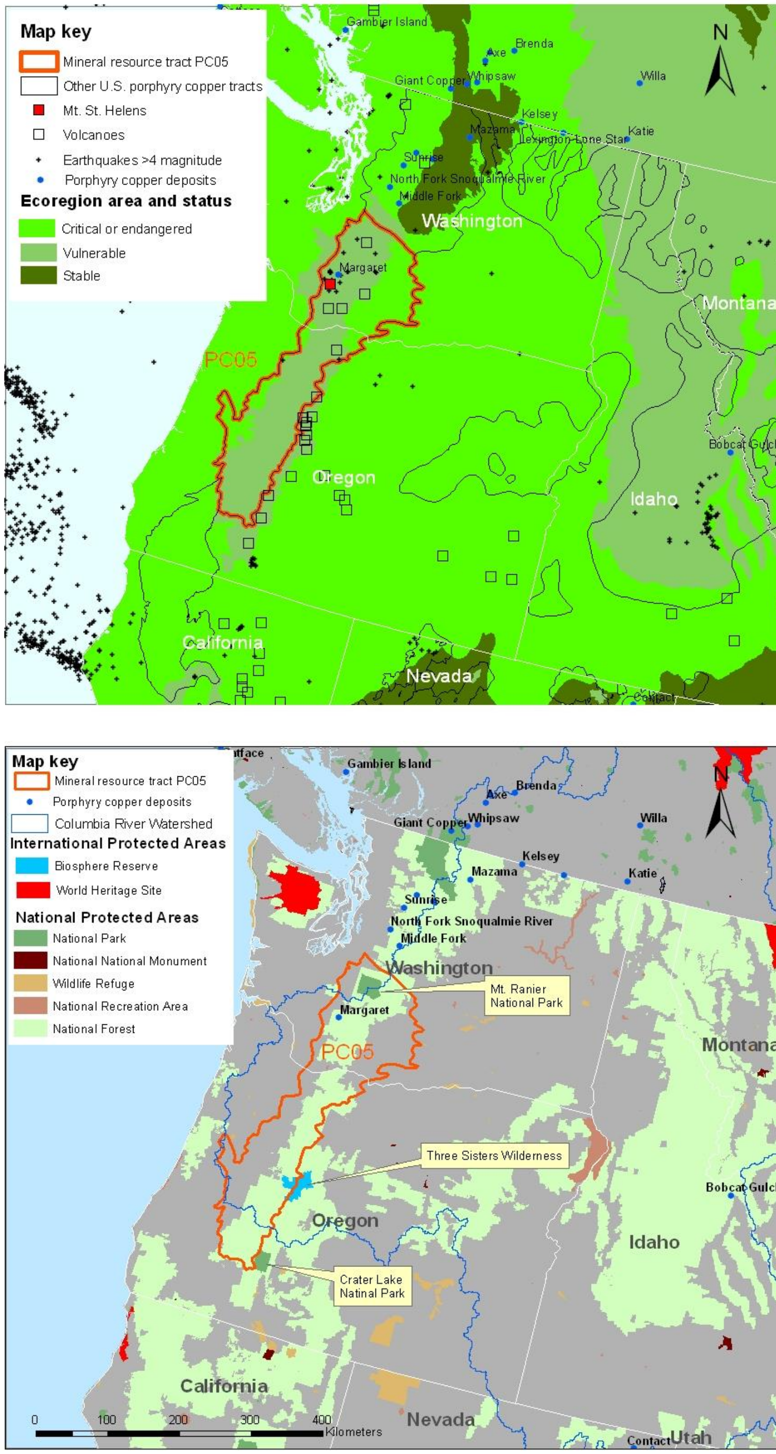

Figure 8. Applications of mineral resource assessment information for environmental planning. A, Ecororegion status and natural hazards. B, Protected areas. Data sources: Hearn et al., 2000; Singer et al., 2005b; Schruben, 2002; WPDA Consortium, 2005; World Wildlife Fund, 2005.

The term "geoenvironmental model" was coined in an effort to incorporate information concerning the environmental signatures of different mineral-deposit types into mineral deposit models for use both in mineral-resource and mineral-environmental assessments (Plumlee and Nash, 1995). A preliminary compilation of descriptive geoenvironmental models (du Bray, 1995) includes some of the deposit types covered by the global assessment. The geoenvironmental models are tools that can be used to predict and plan for the environmental consequences of future mining, as well as to evaluate, plan, and monitor environmental remediation for past mining.

Water resources

Watersheds are a basis for freshwater management worldwide because they provide society with a variety of goods and services ranging from clean water to fisheries and flood protection. Data are available on a watershed basis for a number of issues relevant to sustainable development (World Resources Institute, 2003):

- land cover and use;
- basin indicators, such as population density, numbers of large cities, numbers of dams; and
- biodiversity information and indicators, including numbers of fish and amphibian species, endemic bird areas, and percent protected area.

Mineral resource tracts can lie within a single watershed or span a number of watersheds. Conversely, multiple tracts for multiple deposit types also can lie within a single watershed. Tract PC05, for example, mainly lies within the Columbia River Basin (Fig. 8b). The Columbia River Basin watershed extends into Canada and includes parts of several tracts that are permissive for the occurrence of porphyry Cu deposits. When the Canadian part of the North American assessment for Cu is completed, mineral resource tracts will be available for the entire watershed. By combining mineral resource tracts with watershed information, the global assessment could help identify future mineral resources in regions with water supplies adequate to support development (or mining) and with hydrologic and geologic characteristics best able to maintain water quantity and quality during and/or after mineral development. Such an assessment also has potential to identify types of mineral deposits and climates least likely in combination to results in serious environmental problems (Briskey et al, 2002).

Conclusions

The global mineral resources assessment will provide a consistent, comprehensive level of information and analysis of undiscovered global nonfuel mineral resources. The assessment results will provide all nations with a regional and global context for planning sustainable development, evaluating their known and undiscovered nonfuel mineral resources, designing new mineral exploration, anticipating and preventing environmental problems, and making land-use decisions.

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