U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

# Agenda, extended abstracts, and bibliographies for a Workshop on Deposit Modeling, Mineral Resources Assessment, and Their Role in Sustainable Development

31st International Geological Congress

Edited by


U.S. Geological Survey

Joseph A. Briskey[1] and Klaus J. Schulz[1]



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Prepared in cooperation with:

Deposit Modeling Program

International Union of Geological Sciences

United Nations Educational, Scientific, and Cultural Organization





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# 31st INTERNATIONAL GEOLOGICAL CONGRESS

## WORKSHOP ON DEPOSIT MODELING, MINERAL RESOURCE ASSESSMENT, AND THEIR ROLE IN SUSTAINABLE DEVELOPMENT

**Sponsored by:**
**IUGS-UNESCO Deposit Modeling Program**
**and the**
**United States Geological Survey**

**Instituto Militar de Engenharia, Room 3001**
**Praca General Tibúrcio**
**80 Praia Vermelha**
**Urca, Rio de Janeiro, RJ**

**August 18-19, 2000**

# AGENDA


**Convened b**
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# WORKSHOP AGENDA

## FRIDAY, AUGUST 18, 2000

**Morning**

8:30: Introduction-Welcome to Workshop (Klaus Schulz & Joe Briskey, U.S. Geological Survey)

8:45: Welcome from IUGS/UNESCO Deposit Modeling Program and the U.S. Geological Survey (Kate Johnson, U.S. Geological Survey)

9:00: Global Nonfuel Mineral Resources and Sustainability (F.-W. Wellmer, Bundesanstalt für Geowissenschaften und Rohstoffe/Federal Institute for Geosciences and Natural Resources, Germany)

9:45: Break

**SESSION I: USES OF A GLOBAL MINERAL MINERAL RESOURCE ASSESSMENT (Session Chair: Charles 'Skip' Cunningham, U.S. Geological Survey)**

***A: Environmental Perspectives***

10:15: The contributions of geologic information to economic, social and environmental sustainability (Deborah Shields, United States Forest Service)

10:45: Environmental planning issues and a conceptual global assessment of undiscovered nonfuel mineral resources (Joe Briskey, U.S. Geological Survey)

11:15: Global biodiversity hotspots and resource development (Penny Flick, Conservation International)

11:45: Discussion

12:00 Lunch

**Afternoon**

***B: Economic and Social Development Perspectives***

1:30: Sustainable development and nonrenewable resources—A multilateral perspective (George Nooten, United Nations Development Program)

2:00: Mineral resources and economic development (Gotthard Walser, World Bank)

2:30: Economics, ecology, and sustainable development of mineral resources in Siberia (A. Kanygin, United Institute of Geology and Geophysics of the Russian Academy of Sciences)

3:00: Break

***C. Mineral Supply Perspectives***

3:30: Mineral supply and demand into the 21st century (Steve Kesler, University of Michigan)

4:00: Global Mineral Exploration and Production – the Impact of Technology (Michael Doggett, Queens University, Canada)

4:30: Global Mineral Exploration—Industry Perspective and Availability of Information (Greg McKelvey or Rich Leveille, Phelps Dodge Corporation)

5:00 Discussion

## SATURDAY, AUGUST 19, 2000

**Morning**

**SESSION II: MINERAL ASSESSMENT METHODOLOGIES (Session Chair: Walt Bawiec, U.S. Geological Survey)**

8:30: Deposit models and their application in mineral resource assessments (Don Singer, U.S. Geological Survey)

9:00: Estimating amounts of undiscovered mineral resources (Don Singer, U.S. Geological Survey)

9:30: Break

10:00: Metallogenesis and tectonics as an integral part of the mineral resource assessment process (Warren Nokleberg, U.S. Geological Survey)

10:30: Discussion

**SESSION III: DATA NEEDS AND AVAILABILITY (Session Chair: Mike Foose, U.S. Geological Survey)**

10:45: Digital geology of the world (Lesley Chorlton, Geological Survey of Canada)

11:15: Status of metallogenic mapping in the world today (Erik Hammerbeck, Council for Geoscience, formerly the Geological Survey of South Africa)

11:45: Lunch

**Afternoon**

1:00: Databases of known deposits: World Minerals Geoscience Database Project (John Wood, Geological Survey of Canada)

1:30: The Mineral Databases of the U. S. Geological Survey (Bruce Lipin, U.S. Geological Survey)

2:00: Break

**SESSION IV: EXAMPLES OF LARGE REGION ASSESSMENT (Klaus Schulz and Joe Briskey, U.S. Geological Survey)**

2:30: U.S. Geological Survey National Mineral Resource Assessment—An Estimate of Undiscovered Gold, Silver, Copper, Lead, Zinc Remaining in the United States (Klaus Schulz, U.S. Geological Survey)

**SESSION V: WORKSHOP SUMMARY AND DISCUSSION (Klaus Schulz and Joe Briskey, U.S. Geological Survey)**

3:00: Review—Summary—Discussion (Klaus Schulz and Joe Briskey, U.S. Geological Survey)

# RELATED POSTER AND ORAL PRESENTATIONS:

**"Where will the world's future mineral resources come from?"**

**Poster Presentation**:
August 16, 2000
1:00---5:30 p.m.
Booth C56

**Oral Presentation**
August 17, 2000
General Symposium 13-3 – Earth Minerals
Room B-1

# 31st INTERNATIONAL GEOLOGICAL CONGRESS

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## ABSTRACTS AND BIOGRAPHIES


**Edited by**
**Joseph A. Briskey**
**U.S. Geological Survey**

# Environmental planning issues and a conceptual global assessment of undiscovered nonfuel mineral resources

**Joseph A. Briskey, Klaus J. Schulz, John P. Mosesso, Lief R. Horwitz, and Charles G. Cunningham**

U.S. Geological Survey
Reston, Virginia, U.S.A.

Global demand for mineral resources probably will continue to increase for the foreseeable future because of the continuing increase in global population and the desire and efforts to improve living standards world wide. "Industrialization is central to economic development and improved prospects for human well-being….A substantial share of industrial growth in developing countries revolves around the transformation of raw materials into industrial materials" (World Resources Institute and others, 1998, p. 51).

Our ability to meet the continuing and growing demand for minerals is greatly affected by concerns about possible environmental degradation associated with minerals exploration and production, and by competing land uses. The sustainability of nonfuel mineral production and supply is a function of the location, availability, and efficient use and reuse of mineral resources while minimizing adverse environmental affects and maximizing economic and social benefits to all stakeholders. Leaders in the mining industry also are promoting the importance of economic, environmental, and social values and responsibilities of and to sustainable development (James, 2000,1999; Wilson, 2000).

There are no indications of global shortages of nonfuel mineral resources in the predictable future. However, unanticipated and therefore unplanned growth in mineral exploration and development, especially in sensitive environments, may lead to further fragmentation and destruction of habitats required for the long-term maintenance of key plant and animal communities, and to an overall reduction in ecosystem health. Increasingly, human populations and their activities such as mining "are disturbing species and their habitats, disrupting natural ecological processes, and even changing climate patterns on a global scale" (President's Committee of Advisors on Science and Technology, 1998, p. xiv). "We are modifying physical, chemical, and biological systems in new ways, at faster rates, and over larger spatial scales than ever recorded on earth" (Lubchenco, 1998). "If current trends continue, humanity will dramatically alter virtually all of Earth's remaining natural ecosystems within a few decades" (Daily and others, 1997).

Informed planning and decisions concerning biological sustainability and resource development require a long-term perspective and an integrated approach to land-use, resource, and environmental management worldwide. This, in turn, requires unbiased information on the global distribution of identified and especially undiscovered resources; the economic, social, and political factors influencing their development; and the environmental consequences of, and requirements for, their utilization.

The world's present approach to land and resource planning is piecemeal and haphazard. For example, mineral development is prohibited or has been proposed to become prohibited in large parts of the world, including: Antarctica; the Arctic Islands; numerous national and international parks, wildlife preserves, and wilderness areas; tropical rainforests; temperate old-growth forests; a variety of alpine and desert regions; and various other sensitive or endangered habitats, ecosystems, scenic vistas, and roadless areas. Concomitantly, as countries grow and develop, mining becomes increasingly unwelcome at home. Sources of future mineral supply rapidly are becoming more restricted while the world community appears to be devoting little effort to identifying, and assuring access to, areas of future mineral supply that can best sustain the environmental effects of mining.

Highly industrialized societies in particular have a responsibility to provide information and assist in planning global mineral development and ecosystem sustainability. These economies use tremendous amounts of materials per capita: 45 to 85 metric tons/person/year in one study (World Resources Institute and others, 1998). The use of these materials requires moving or processing huge amounts of natural resources not actually used in the final product. As much as 50 to 75 percent of this hidden materials flow, and associated environmental affects, often take place in other countries (World Resources Institute and others, 1998).

Consequently, the United States and other highly industrialized societies should help initiate and participate in an international assessment of the probable locations, amounts, and types of the world's remaining undiscovered nonfuel mineral resources in relation to sensitive ecosystems and habitats so that mineral development can be encouraged in those areas best able to sustain the environmental effects of mining and mineral processing, and discouraged or carefully managed in sensitive areas. If the choices for future supplies of some minerals prove to be limited mostly to areas where maintaining ecosystem health and sustainability will be difficult, international cooperation could be accelerated to: (1) optimize materials flows and recycling of materials derived from these minerals; (2) promote research into alternative materials and technology to replace these minerals or minimize their use; and (3) develop advanced new mitigation techniques for exploration, mining, and processing for these minerals.

"An electorate that does not understand the natural world or the nature of the tradeoffs that must be made in managing it wisely and sustainably cannot make informed decisions" (President's Committee of Advisors on Science and Technology, 1998, p. xviii).

**A feasibility study**

In response to growing concern about the global sustainability of nonfuel mineral production and environmental quality, and the concomitant increase in demand for global mineral-resource information, the U.S. Geological Survey has initiated a project to evaluate the feasibility of conducting global mineral-resource assessments.

Is it possible, as well as practical and useful, to conduct a global assessment of undiscovered nonfuel minerals resources? This feasibility study is intended to answer this and other questions by evaluating how many people with what kinds of expertise would be needed to do such an assessment, and how they might best organize themselves. How long would the assessment take? What data are needed? Are the data available? At what cost? Can the data be used as they are, or do they need substantial compilation or recompilation? How should mineral commodities be prioritized for assessment? How would a global assessment be used and by whom? What would it cost to undertake and complete such an assessment? What assessment methods are available; which are best suited for this type of assessment; do new methods need to be developed? Among methods being evaluated is the established USGS quantitative mineral-resource assessment methodology that produced the assessment of conventional undiscovered deposits of gold, silver, copper, lead, and zinc remaining to be found in the United States (U.S. Geological Survey Minerals Team, 1996).

**Information and data requirements**

The feasibility study initially has focused on three types of data that will be needed for a global assessment: (1) maps showing the locations, sizes, and geologic types of known mineral deposits and occurrences; (2) maps showing geologic terranes/tracts permissible for the occurrence of undiscovered mineral deposits type; and (3) as much information as possible about mineral exploration history. Much of the exploration information resides in the corporate memory and files of the mining industry. Participation of the private sector is crucial for this reason, as well as for assistance in all stages of the assessment.

**Conceptual products and some potential uses**

A discussion of a conceptual global mineral-resource assessment and related products is intended only as a starting point for discussions of many possible products and uses. Global assessments potentially are of great importance in helping us recognize, discuss, manage, and minimize or prevent environmental trade-offs and impacts associated with mineral exploration and mining.

<u>Biodiversity and sensitive habitats</u>. What are some examples of the potential consequences of mineral development at high latitudes as compared to low latitudes? At high latitudes, impacts of mineral development on biodiversity potentially would be smaller and people would be less likely to stay after mining had ceased. However, disturbed ecosystems are likely to require a longer time to recover. Some of the undiscovered resources in S. E. Asia occur in endangered tiger habitat. Discovery and development of predicted undiscovered Sierran kuroko-type massive sulfide deposits in the foothills of central California have the potential to adversely affect endangered species habitat and vulnerable plant communities delineated by the USGS GAP Analysis Program. World tin resources in differing geologic settings have a high spatial correlation with the distribution of biodiversity "hotspots" as defined by Conservation International (Mittermeier and others, 1999).

<u>Land Use</u>. Habitat disturbance and fragmentation resulting from infrastructure development is a principal cause of species extinction. Ideally, mineral exploration programs would disturb only those areas with a high probability of containing an economic deposit (Sweeting and Clark, 2000). Mineral exploration and development also might be encouraged in regions where infrastructure already is in place. Maps and other information showing the types and density of infrastructure development and other land uses would be important ancillary data bases for using a global mineral assessment. Maps showing areas already off limits to mineral discovery and

development would help examine and analyze alternative sources of supply and compare relative environmental impacts and trade-offs.

Water resources and quality. The boundaries of major drainage basins are international. A global mineral assessment could help identify future mineral resources in regions with adequate water supplies and with hydrologic and geologic characteristics best able to maintain water quantity and quality during and after mineral development. Such an assessment also has the potential to identify types of undiscovered mineral resources and climates least likely in combination to cause environmental problems.

**In summary**, without the kinds of information that could be provided by a global mineral resource assessment, the world will unknowingly foreclose future mineral supply options that might otherwise have resulted in reduced environmental degradation, lower economic costs, and improved social benefits.

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# Trends in mineral-resource, environmental, and societal planning and decisionmaking—A discussion

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*The following is from a series of informal email exchanges between the authors during the period June 12-26, 2000. The views and any conclusions expressed by the authors herein are theirs alone and do not necessarily reflect those of their respective governments.*

**BRISKEY**: Klaus Schulz and I are convening a workshop sponsored by the IUGS/UNESCO Deposit Modeling Program and the U.S. Geological Survey on "Deposit Modeling, Mineral-Resource Assessment, and Their Role in Sustainable Development" at the International Geological Congress (IGC) in Rio de Janeiro, Brazil, August 18-19, 2000. We are looking for speakers….

Global demand for mineral resources continues to increase because of increasing global population and the desire and efforts to improve living standards worldwide. The ability to meet this growing demand for minerals is affected by the concerns about possible environmental degradation associated with minerals production and by competing land uses. Informed planning and decisions concerning sustainability and resource development require a long-term perspective and an integrated approach to land-use, resource, and environmental management worldwide. This, in turn, requires unbiased information on the global distribution of identified and especially undiscovered resources, the economic and political factors influencing their development, and the potential environmental consequences of their exploitation.

The purpose of the IGC workshop is to review the state-of-the-art in mineral-deposit modeling and quantitative resource assessment and to examine their role in the sustainability of mineral use. The workshop will address such questions as: Which of the available mineral-deposit models and assessment methods are best suited for predicting the locations, deposit types, and amounts of undiscovered nonfuel mineral resources remaining in the world? What is the availability of global geologic, mineral deposit, and mineral-exploration information? How can mineral-resource assessments be used to address economic and environmental issues? Presentations will include overviews of assessment methods used in previous national and other small-scale assessments of large regions as well as resulting assessment products and their uses.

Results from the IGC workshop will help to determine whether it is possible, as well as practical and useful, to conduct cooperative international assessments of global undiscovered nonfuel mineral resources.

**LAMBERT**: I have done a lot of thinking about Australia's resource base, and the world’s. I see no long-term shortfalls in the foreseeable future, provided there is reasonable resource access (not too much land "locked away").

I am intrigued about your concept of a cooperative international research effort to assess the locations and amounts of the world's remaining undiscovered nonfuel mineral resources. The project sounds interesting, but I am wondering how it would be used given that resource development is usually a commercial decision that has to be approved by the regulatory authorities in the country where the proposed mine is located. I would be concerned if your aim was to somehow attempt to influence where mining should be able to take place outside the US. I will read your brief with interest.

**BRISKEY:** I agree with your comments that there are no looming global shortages of nonfuel (or fuel) minerals in the foreseeable future. Nonetheless, I’m also firmly convinced that access to, and availability of, mineral resources around the world will become progressively more restricted and regulated in the next century and beyond because of growing, global environmental concerns. This also was the consensus of a constructive and informative environment and resource conference I attended in Taos, New Mexico, two years ago with other representatives of the resource and environmental communities. The conference report was published in: Environmental Geosciences, 1999, Meeting Societal Resource and Environmental Requirements into the 21$^{st}$ century: American Association of Petroleum Geologists Division of Environmental Geosciences, Environmental Geosciences Special Issue, v. 6, no. 4, pp. 163-214.

Large amounts of mineral-rich land are being, and will continue to be, withdrawn from mineral entry in many, if not most, of the countries of the world. Without some kind of global assessment of undiscovered resources, these withdrawals will occur without consideration of alternative sources and their associated relative impacts on the local as well as global environment. Indeed, it is certain that some mineral-resource lands being withdrawn today are in fact the "best" place(s) in the world from which to obtain some minerals with the least relative environmental impact. We believe individual nations, companies, organizations, and the world will be better served if information about global distribution of undiscovered mineral resources and their environmental contexts is available when such decisions and trade-offs are debated and made. This will be an enormous, long-term undertaking. It is not too early to begin an international effort to compile and interpret global mineral-resource information to assess the likely occurrence and amounts of undiscovered mineral resources in a variety of natural environments around the world.

Individual countries no longer are completely free to develop their natural resources at the expense, real or perceived, of environmental quality, including clean air and water, and protection of endangered species, biodiversity, the global climate, and the ozone layer. "Free trade" no longer includes many resources such as whales, ivory, seals, furs, eagle feathers, and other parts of endangered species, to name only a few. The United States, for example, has trade laws in place requiring that international trade decisions take into account associated impacts on the environment. The World Trade Organization is supposed to allow environmentalist import bans, so long as the reason for them is not disguised protectionism. My tuna no longer is flavored with dolphin, nor my shrimp with turtle. International pressure to protect the environment in all its aspects will only grow with time. This train has left the station and is disappearing into the distance.

Our early discussions about efforts to conduct and use global nonfuel mineral-resource assessments have been received favorably by environmental organizations. Moreover, the mining industry is beginning to recognize, accept, and respond to growing social and environmental concerns about mining and its effects (again, real and perceived) on society, including the environment (e.g., James, Patrick M., 1999, The miner and sustainable development: Mining Engineering, June 1999, p. 89-92; and Wilson, Sir Robert [Executive Chairman of Rio Tinto], 2000, New frontiers in mining—Meeting 21st century challenges: Mining Engineering, v. 52, no. 6 (June), p. 72-75).

**LAMBERT:** I agree about the increasing pressures on resource access - this is an issue that I deal with a lot in my day-to-day activities, and it was clearly recognised by CEOs of major minerals companies when they agreed recently on the need for a World Mining Initiative, which is now up and running.

The question I have is whether the strategic issue of resource access is best tackled as an international minerals-focussed project, or by action within individual countries to try and achieve responsible multiple and sequential land use, using evidence-based risk assessment, and a multi-disciplinary, multi-agency approach. The latter approach is being pursued in Australia - for example, we have succeeded in having mineral potential taken into account in land use decisions, most notably in a recent process looking at reserves in forest lands, and in the decision to allow uranium mining at Jabiluka (which is surrounded by the World Heritage listed Kakadu National Park). This work has involved the development and use of decision support systems to integrate minerals values with other values to reach informed, transparent decisions. I will be referring to this in a keynote presentation that I will be giving at the International Consortium of Geological Surveys meeting, at IGC in Rio, probably during the afternoon of 15 August.

**BRISKEY**: Thanks very much for your additional comments and insights. I hope we have the chance to delve more deeply into some of the critical issues you raise. One of the things we'd like to know more about is the "World Mining Initiative." What is it and who is involved from your perspective? What does "up and running" mean for the initiative? Can you direct us to a website or publication explaining this effort in some detail?

The rational and logical land- and resource-planning process you allude to would be the ideal answer to resolving preservation and mineral-development conflicts nationally if it weren't for international trade, and if we weren't dealing with people and politics. In 36 years in the United States, continuous attempts, (some Herculean and many by law) to implement such processes have fallen short or failed in most cases. Any "successes" were, in retrospect, only temporary; the passage of time largely is sweeping or has swept them away. Perhaps, though, you will have better luck in Australia. In the final analysis, however, when the choice is mining or preserving the environment, the environmental arguments, and the emotional pleas to save the plants, animals, scenic wonders, unspoiled vistas, etc., nearly always prevail, or will eventually. As our population grows and expands geographically, fights to save dwindling open spaces and threatened environments will only increase. After all, we always can get minerals from somewhere else, including other countries, right?

I've been involved as an economic geologist in this process on and off for 25 years, and managed the USGS National Mineral Resource Assessment Program for six years. For two years, I also worked on these and related issues while a member of the personal staff of a U.S. Senator (from a “mining State”), and while on the staff of the U.S. Senate Committee for Energy and Natural Resources. I see little or no chance that land, mineral-resource, and environmental planning on a national scale will succeed as you hope, though I greatly admire your noble efforts and logical instincts.

"Minerals can always be imported." Nevertheless, one of the presently unrecognized or largely unacknowledged problems with imported minerals is that they may come from environments (ecosystems, habitats, etc.) that are more sensitive than those being debated for domestic mineral development. Mining in some sensitive foreign sites may have greater deleterious affects on domestic environmental quality (e.g., through global warming, reduced biodiversity, and threats to endangered species) than mining some equivalent domestic deposits in less sensitive environments at home. Nonetheless, there is no information available with which to recognize and respond to the global interconnectedness of resource development and a multitude of related environmental concerns, both global and domestic, which must be dealt with. This is what our global mineral-assessment proposal is all about. I don't think the issues of resource access and environmental protection are best tackled internationally/globally, I think this is the ONLY way they can be successfully tackled.

It is true that the minerals sector always can point to a few "successes." Nonetheless, the trend overwhelmingly is for protecting and preserving the environment, ecosystems, sensitive and endangered species and habitats, and biodiversity; and is against mining (see above paper by Wilson, 2000). This trend continues to grow in developed countries and is beginning to arise in developing countries. Moreover, the citizenry in some developed countries is beginning to rebel at what they see as unbridled resource (and social and environmental) exploitation in developing countries. The recent violent protests in Seattle (USA, State of Washington) against the World Trade Organization, World Bank, and United Nations, among others, are examples.

Discounting an unexpected crisis caused by an unpredicted worldwide shortage of nonfuel minerals, I see no reason to expect these trends to change in the next century. Nonfuel mineral resources will continue to be an issue for the average citizen only when mining threatens or causes environmental disaster. Providing information to help address the social and environmental aspects of mineral exploration and development is the most prominent, and perhaps the only seriously supportable, role for mineral-deposit and mineral-resource research I can see anywhere on the horizon.

**LAMBERT**: The *Global Mining Initiative* (GMI) is a CEO-led program to provide sustainable leadership for the mining and minerals industry in the areas of economic, social and environmental performance. It is not meant to be a PR (public relations) exercise, advertising campaign, or educational exercise. It is about listening, learning and engaging. The GMI is about turning words into actions.

The GMI grew out of informal discussions between a small group of CEOs who moved to convene a meeting to discuss issues around the reputation of the mining industry and the implications of sustainable development. A core group of 9 companies met in October 1998, and the project is now supported by 27 companies.

The major focus of the GMI is an analysis of the issues the industry faces, and this is being achieved by a worldwide study called Minerals, Mining and Sustainable Development (MMSD), which by design is independent of the industry. Further information can be obtained at http://www.iied.org/mmsd/.

After Rio, I intend travelling on to Europe, and this project is one I plan to learn more about. In summary, the MMSD Study is meant to generate:

- Broadly based and authoritative analyses of key issues which arise from people's expectations of sustainable development;

- The foundation for the new relationships and partnerships which the scale of the challenges demand;

- More active engagement between the industry and others in order to understand the issues better, and the identification of the priorities as we go forward; and

- Clarification on where the boundaries lie for action by different participants.

While the study is global in nature, it will be managed by smaller groups on a regional basis. A report on the study is planned for late 2001.

It is good to see the industry taking global action of this nature. It is often hard to know where the responsibilities of governments end and the industry has to take over. I think that this is all acknowledging that the industry realises it has got to take on more of the effort to ensure that it has access to an adequate supply of resources in the future.

As an aside , I note that this is consistent with what we have been trying to do in AGSO in pursuing responsible multiple and sequential land use. This is trying to sustain the principle that exploration and mining are not ruled out (except in most National Parks and other nature reserves, which amount to less than 7% of the land area of Australia), but are considered on their merits on a case by case basis. To achieve this, one has to move on from the "them" and "us" approach, to establishing a reasonable working relationship between all key players. I see this as complementary to the approach of the GMI/MMSD.

As Don Singer, at least, will be aware, my Group has been conducting mineral potential assessments of forest regions in southeastern and southwestern Australia, and these assessments have been integrated with other values in reaching decisions on reserve design. We have been using a qualitative approach based generally on the USGS approach, and we are now extending this to a Mineral Potential of Australia Project, which will have something of a focus on identifying the mineral potential of the remoter parts of Australia (greenfield regions).

I can't help thinking that I have now prepared a summary of what I would have presented had I been available for your workshop.

**BRISKEY**: The summary you've provided of the "Global Mining Initiative" is very informative and gives one reason to be somewhat optimistic that the industry is beginning to seriously recognize, and especially respond to, growing environmental and sociological concerns about mining. Thanks very much for taking the time to send it. I agree that the ball is in industry's court; it's been there a long time; it's good to see signs that they are starting to run with it together. [For additional information and perspectives on the GMI, readers also are referred to the recent paper “New frontiers in mining—meeting 21$^{st}$ century challenges—theme of SME Annual Meeting:” Mining Engineering , v. 52, no. 6 (June), pp. 70-78 (especially pp. 73-74)].

I will be very interested to watch the progress of your forest studies and any related land-use decision making. The application and practical effect of resource management planning and multiple-use concepts in U.S. National Forests is in decline. For example, calls to halt logging throughout all of our National Forest system started in 1995 or earlier and are growing. I foresee the time, soon, when our national forests will become inviolate preserves. This no doubt will take a few years longer in Australia.

**Digital Geology of the World, World Minerals Geoscience Database Project**

**Lesley Chorlton**

Mineral Resources Division
Geological Survey of Canada

The primary goal in developing an attribute database and geospatial feature data set for the generalized geology of the world (GGW) is to enable geologists to extract easy-to-use custom data sets for resource assessment, environmental modeling, tectonic reconstruction, and visualization using custom programs or interactive graphical query interfaces. The GGW is a 'working model' that is periodically tested in terms of its ability to represent the most globally significant geologic elements encountered in standard regional sources and its applicability for these purposes, and adjusted accordingly.

The geological features described by the GGW data set are major fault traces and bedrock domains. The geospatial (GIS) representation of each feature is linked to one or more top level attribute records, because the activity on any major fault is commonly multi-stage, and each bedrock domain, when generalized to the level required for global visualization, may contain multiple 'units' (bedrock age-rock type entities). Each fault stage has one age range, one or more common names, one tectonic significance, and potentially several discrete displacement components. Each bedrock entity has one age range, one or more names, and many rock-type components. Rock-type components fall into broad categories: sedimentary, volcanic, intrusive, volcano-sedimentary, metamorphic, and tectonic. Each component category leads to its own detail tables. The last three categories are dual in nature, and may lead to multiple detail tables, whereas sedimentary, volcanic, and intrusive components will each lead only to one detail table record. Detail tables contain general classifiers such as general intrusive suite and main magma series for intrusive rocks, and compositional descriptor, magma series, and depositional setting for volcanic rocks. These will be the main descriptors used for filtering rock types, and must contain generalized terms that can be applied with confidence worldwide. The presence of significant metalliferous sediment, evaporite, oil or gas, or coal is flagged in the sedimentary detail table, and likewise metalliferous sediment is flagged in the volcanic detail table. Individual lithologies are named in subtables because there may be many of them for each component. Similarly, multiple internal structures, external forms, and environments are housed in subtables.

Categories of information for each bedrock domain or fault came from which data source, catalogued in an independently indexed reference database, are captured in junction tables. This system is used for verification and guidance when updating the database, and will ultimately help maintain confidence in the data over the long term.

Geological provinces, belts, basins, platforms, and other elements can be placed in a tectonic 'event' context, with their own age range and tectonic setting information. Province records are now independently indexed in a single table, and will be carefully linked to their component bedrock domain entities, as well as to their references, using junction tables. The spatial framework for bedrock domains will serve as the geological provinces' GIS component.

The spatial components of the bedrock domains and fault data sets are generalized from more detailed geological map data sources. These sources are increasingly available in digital GIS format; eventually it will be possible to have a nested series of geological feature frameworks at several scales. For the global generalization level, the maximum distribution of elements of interest is more important than precise geometry. Methods for updating the generalized global geology directly over the digital source, and semi-automating the aggregation of bedrock units into the attribute database, are being actively investigated. The cumulative area of each entity derived from the detailed map and attached to a given bedrock domain is computed by the GIS software during the aggregation process. The cumulative area can be captured in the top level attribute table so that despite the spatial simplification, a crude level of spatial quantification can be achieved.

The GGW data set is now populated mainly with information about age range and very general categories of bedrock domain and fault. Intrusive suite and volcanic composition have also been added where they are depicted in the regional geological source maps. It will take time and, ideally, input from more than one geological working group to add uniform coverage to the deeper levels of the database. Any group that shoulders the task of inputting global coverage of some specialized category of information would be the authors of any thematic output data sets and publication emphasizing that information.

To test the usability of the database in this form, query routines have been written to automatically provide thematic output that is easy for non-GIS proficient geologists to view and manipulate with desktop software. These output files are flat in structure but customized for particular purposes by the queries that were applied to create them. The same technique could be used to produce layers for tract assessment purposes.

The province data set may presently offer the most useful framework for global resource modeling, and could be used in parallel with mineral deposit databases that will house similar information. Because it is independently indexed, it could be built up by an external group of global tectonic specialists or by working groups for different areas, before being linked to the bedrock domain entities, and hence to spatial distribution.

# Global Mineral Exploration and Production – the Impact of Technology

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Many of the largest, highest grade, closest to surface, closest to market mineral deposits have been depleted or are currently in production. Over the next half century, the competition for land use among an ever-increasing population will become fierce. Mining companies struggling to improve the traditional bottom line will be forced to support a triple bottom line quantifying the costs and benefits of environmental and social responsibilities. Under these adverse conditions, the ability of the international mineral sector to find and produce required amounts of metallic, non-metallic, and fuel commodities hinges on technological innovation. While it would be naïve to blindly trust in technology to resolve these issues, it would also be imprudent to ignore the past contributions of technology to an industry that ranks among world leaders in productivity. An analysis of global mineral exploration and production over the past 50 years reveals some interesting trends and indications as to where the mineral sector is headed in the years to come.

Global exploration expenditure for gold and base metals has increased significantly on a decade by decade basis over the past 50 years increasing from approximately $3.5 billion in the decade of the 1950s to more than $28 billion in the decade of the 1990s. (All values are in constant 1999 US dollars). Over the same period of time, the output of gold and base metals also increased significantly. Using a metal mix of gold, silver, copper, lead, molybdenum, nickel and zinc, average output in the 1990s was 225% higher than in the 1950s. Thus, to a certain extent, the significant increase in exploration expenditures reflects the fact that more and/or larger deposits had to be discovered to meet increased demand for mineral commodities. With respect to base metals, this certainly appears to be the case. Exploration expenditure for base metals per unit of output has been nearly constant over time. For example, if base metal expenditures are divided by the total copper and zinc production on a decade by decade basis, the resulting exploration cost per pound of metal is shown to have remained quite constant (in the range of $0.02 – 0.03 per pound) over the 1950-1999 period. The exploration cost per ounce of gold production, on the other hand, displayed an increasing trend for the 1950s to the 1980s peaking at more that $35/oz before decreasing somewhat in the 1990s.

In the non-renewable resource sector, changing discovery costs over time should provide a measure of the trade-off between depletion on the one hand and technological advances on the other. Increases in discovery costs would suggest that the effects of depletion are not being offset by technological gains. On the other hand, steady or decreasing discovery costs over time indicate that technology is offsetting the impact of depletion. Based on this simple concept, it would appear as if technology advances in the base metal sector have been sufficient to offset depletion effects during the past 50 years. Gold discovery costs have increased substantially but the results are somewhat misleading due to the extreme volatility in the gold market over the 50-year period.

Another measure of the long-term trade-off between depletion and technology is provided by real commodity price trends. Most mineral commodity prices have displayed a decreasing trend in real terms for much of the past 50 years. Again, this suggests that technology has been more than able to compensate for depletion during this period of time. Taken in conjunction with increasing output over time, the decreasing price trend reflects the highly productive nature of the mineral industry. If commodity prices are combined with metal output, the gross value of production for the industry can be calculated. The trend in the value of production should reflect the net impact of increasing output and decreasing prices. For the entire gold and base metal industry, the value of production increased sharply in the early decades of the study period. From the 1970s forward, however, the value of production has been essentially flat. This means that over the past three decades, increases in metal output have been almost exactly offset by decreases in metal prices. In an industry which espouses growth as one of its main objectives, a flat trend in value of production represents an immense hurdle. Furthermore, it does not suggest that the mining industry has been in any substantial way impacted by the continued depletion of deposits.

As evidenced above, trends in discovery costs, metal prices, and value of production suggest that technology has been able to more than offset any depletion effects during the past 50 years. Can it be assumed that these same trends will continue for the foreseeable future or are new external factors at play which will fundamentally alter the depletion-technology balance? To address this issue, it is necessary to consider the technology factors underlying the trends in costs, prices, and output.

While there have been important technological innovations at all stages of the mineral supply process from exploration to development to production to reclamation, those having the greatest impact have been in one way or another related to either scale of operations or processing and metallurgical changes.

With respect to scale, much of the increased output of metals on a worldwide basis has resulted from the development of huge open pit operations. Technological advances in mining and processing equipment have enabled enormous increases in mine capacity with resulting decreases in unit operating costs and cut-off grades. A survey of copper mines provides a good example of the staggering increases in capacity. The 10 largest copper mines in terms of annual capacity in 1978 could produce a total of 2.1 million tonnes of copper. Only one mine (Chuquicamata) could produce more than 300,000 tonnes per year. Projected copper production from the 10 largest mines in the year 2000 is estimated at 4.9 million tonnes. Furthermore, 8 of the top 10 producers have an annual capacity exceeding 300,000 tonnes of copper .

The second critical area of technological advance is in metallurgical processing. The advent of heap leaching and solvent extraction electrowinning (SX-EW) has had the effect of cutting out whole sections of processing flow sheets and reducing costs proportionately. Again using the copper industry as an example, in 1980 essentially no copper was produced using SX-EW technology. Estimated SX-EW production in the year 2000 is nearly 20% of total copper production.

The combination of larger scale and cheaper processing has resulted in substantial increases in metal from existing mines. In the USA for instance, copper production in the 1990s achieved levels of production not seen since the late 1970s. All of this increased production resulted from larger scales and new processing methods. No new discoveries were made or developed.

Looking ahead to the next 50 years of metal discovery and production, is the mineral industry asking too much of technology? What are the technological advances which will allow the mineral industry to continue to reduce costs, increase production, improve environmental and social performance, and produce sufficient profits to mollify shareholders?

With respect to technology breakthroughs in the recent past, the trend toward larger and larger scales of operation is unsustainable. The backlash against huge open pit operations has started in developed countries and will certainly spread to other jurisdictions over the next few decades. Furthermore, the economies of scale will begin to diminish at some point as larger and larger operations are established.

On the processing side, the potential for further technological breakthroughs is enormous. New leaching technologies should eventually eliminate the need for smelting and refining of first oxide and then sulphide ores. The possibility of in situ leaching would eliminate the need for moving tonnes of ore and waste to recover small quantities of payable metals. As an intermediate stage, the development of automated mining should allow access to new sources of underground ore.

Will we eventually reach a point where depletion, and environmental and social pressures, drive up costs of production and metal prices so that the U-shaped price curves of natural resource economists are realized? Perhaps. Will it happen in the next 50 years? Unlikely.

# Global Biodiversity Hotspots and Resource Development

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The number of species threatened with extinction far outstrips available conservation resources. This places a premium on identifying priorities. By concentrating on areas where both the need and the potential payoff from conservation measures are greatest, we can prevent the large-scale extinctions which otherwise lie ahead. Conservation International (CI) has identified 25 biodiversity hotspots that represent top priorities for global conservation. These biologically rich areas have high concentrations of endemic species—species restricted to these places and found nowhere else in the world. The hotspots, the majority of them in tropical, developing countries, are highly threatened by human activities, development, and population growth. Cumulatively, the hotspots have lost almost 88% of their original habitat, leaving only 2.1 million $km^2$—an area amounting to just 1.4% of the land surface of the planet. The hotspots contain a staggering 44% of the Earth's plant species and 35% of its vertebrate species. These habitats and their endemic species face a high risk of elimination.

The Center for Applied Biodiversity Science (CABS), a division of Conservation International, is working to protect biodiversity through collaborations with universities, research centers, multilateral agencies, governments, and non-governmental organizations. The development of many new technologies is improving our ability to monitor and understand the economic, demographic, political, climatic, and land-use trends that affect biodiversity. CABS research acts as an early warning system by identifying potential threats to the hotspots before they irreversibly impact biodiversity. Identifying potential areas of resource development, including mineral resources, is an important component of this early warning system. By providing accurate, timely, and useful information to decision-makers, CI and its partners can support them in making sound choices about how best to protect the hotspots.

# Status of metallogenic mapping in the world today

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## Historical background

Although geologists had been preoccupied with the study of mineral deposits since the very beginnings of our science, the concepts of metallogeny and metallogenic maps are less than fifty years old. The debate on what these concepts mean, and how they should be depicted on maps has largely subsided, and there is some convergence towards two dominant schools of thought, i.e. French and northern American, but there are many exceptions or adaptations (i.e. UK, Australia, Canada). A third type, exemplified by Russian maps of the Soviet era, has found less acceptance in view of the complexity of their legends, although some examples have been published only very recently (i.e. Angola and Mozambique). Consensus on this matter is unlikely ever to be reached, although it would help the cause of global resource assessment tremendously.

Personally, we advocate the French legend for its clarity (the symbols are easy to relate to), its descriptiveness, being largely factual rather than interpretative (which is left to the users of the maps), and the cartographic clarity of representation, even in GIS format.

## Metallogeny: culmination of data synthesis

Invariably, metallogenic maps are complex maps, portraying a multitude of data elements on current knowledge about geological processes that may have contributed to the formation of mineral deposits. As such, they represent a most valuable store of information about the mineral potential of countries, regions, or continents. In this point lies both their strength and their Achilles heel. One might expect that metallogenic maps would be regarded as being indispensable tools for mineral exploration, land-use planning, as well as teaching and research in economic geology, but often that does not seems to be the case.

The reason is that metallogenic maps are far too complex to be useful for non-specialist planners and decision-makers. Another reason is that good maps can only be compiled for regions where the geology is well understood and which are reasonably well explored, and at a time long after the often frenzied exploration rushes. So, if metallogenic maps indeed come too late, so to speak, to be indispensable tools for mineral exploration, or remain grossly undervalued in land-use planning and even by the geological community at large, what is their worth?

The obvious answer lies in regional resource assessment. A large number of metallogenic and related mineral maps have been published over the past three or four decades on national, regional, or continental scales. To provide a review of the world-wide availability of such maps is beyond the scope of this paper. Whereas large and medium scale metallogenic maps (say up to 1:250 000) continue to serve a useful purpose to synthesize and document detail of selected mineralised terranes, it is maps on scales of, say 1:1,000,000 and smaller, that lend themselves best to metallogenic analysis. It is important to note, that in order to remain topical and timely, it is in the interest of countries, regions, or continents with emerging mining industries to produce metallogenic maps as a means to attract mining investment.

The Commission for the Metallogenic Map of the World (CGMW) endeavours to promote this cause through its international collaborative projects. Presently, projects carried out under its auspices include the International Metallogenic Maps of Africa, and of South America, both on 1:5 million scale, and it is an ambition to add a map of the Middle-East to this series. In addition, a new thematic global map (1:25 million) of exceptionally large mineral deposits is being compiled, primarily driven by a joint Chinese-Russian research project. A large database on deposits that are to be depicted on this map is being compiled at the Vernadsky State Geological Museum in Moscow, and concomitant Russian research on deep seismic structures is particularly interesting in this context.

The electronic media has changed the face of metallogenic maps during the last decade or so. Since the early eighties, many Geological Surveys started to develop mineral deposit databases, and today GIS and digital map-making are common-place. More importantly, however, is the ability to exchange data and to integrate it more or less at will, with other data sets, and the power to query and manipulate the data and to produce any number of customised products, as a basis for a multitude of research projects and to serve consumer needs.

The strength of present-day metallogenic maps lies in access to digital data sources, and the aforementioned map of Africa is a case in point, with the added vision of being able to seamlessly integrate the data of South America in the near future, and eventually also of the Middle-East, into a compatible database of global expanse.

Access to data and information, copyright, and the exchange of data remain somewhat vexing questions.

## Mineral deposit modeling: the African perspective

Deposit modeling, by definition, refers to a "body of information describing the essential attributes of a class of mineral deposits". A database, such as that of the Metallogenic Map of Africa (MMA), is ideally suited to achieve that objective, in that it not only greatly facilitates the description of definitive ore deposit types, but also their genetic association and their comparison in space and time.

### Descriptive and genetic ore deposit modeling.

The MMA database is based on an advanced GIS data model, comprising various data layers carrying the pertinent data on which the parameters for descriptive and genetic deposit models can be defined, including:

- The main commodities present (first three)
- The morphology (or shape) of deposits and their orientation, if applicable
- The lithostratigraphic setting of the deposit
- Lithology of the host rock
- Environment of formation of the host rock
- Geotectonic environment
- Age of mineralisation
- Type of mineralisation

Although genetic deposit-model-type data are not carried on the database (because of their subjective nature), such models can be easily derived from the available data by association, combination, and interpolation of the various data elements and parameters.

**Metallogenic and geotectonic setting**

The African continent has a complex geologic and orogenic history, briefly comprised of the following main events:

**Archean**. The Archean in Africa is characterized by two major lithological assemblages, namely greenstone belts and high-grade metamorphic terranes. Greenstone belts consist of thick volcano-sedimentary sequences that have suffered low-grade metamorphism. They represent supracrustals to the granitic basement rocks, which originated possibly through three magmatic stages: (i) 3.5-3.2 Ga tonalite/trondhjemite gneisses; (ii) 3.2-2.7 Ga porphyritic migmatite/gneiss; and (iii) 2.8-2.5 Ga syn-to-post-orogenic granites.

Of particular metallogenic interest are the Archean greenstone terranes within the Kaapvaal, Zimbabwean, Zairean, Tanzanian, Chaillu-Ntem, Leo, and Reguibat metallogenic provinces. Mineral deposits associated with greenstone belts include gold, antimony, iron, chromium, nickel-copper and copper-zinc. The lowermost ultramafic units of some of these greenstone belts contain significant deposits of chromite, nickel-copper, and chrysotile asbestos (e.g. Selukwe, Empress, Shangani).

Gold is widely distributed in all the Archean greenstone belts of the continent. However, the most productive and best developed gold deposits occur in the Kaapvaal and Zimbabwe cratons, e.g. Barberton belt, South Africa. Lesser known, but locally important Archean gold deposits occur in Zaire (e.g. Kilo and Moto) and in Gabon. In general, gold is concentrated in structurally-controlled vein deposits that cut basic to intermediate igneous rocks in the marginal, and stratigraphically upper parts of the greenstone belts.

Algoma-type iron formations, associated with the volcanic successions of many greenstone belts, are chemical sediments formed by volcanogenic exhalations and can constitute economic deposits of iron (e.g. Buchwa in Zimbabwe, Nimba in Liberia).

During the late Archean in South Africa, cratonised lithospheric plates developed, resulting in the widespread formation of sedimentary basins, platform sediments, and the development of continental-margin geosynclines at a time when greenstone belts were still forming further north in Africa and elsewhere, i.e. in the time span 3.0-2.6 Ga. The examples on the Kaapvaal are the Pongola Sequence (3.05 Ga), the Dominion Group, and the Witwatersrand and Ventersdorp Supergroups (2.62 Ga).

Syngenetic stratiform gold-uranium mineralization formed associated with placer-type sedimentation in the Witwatersrand basin, South Africa, which was deposited intracratonically on the Kaapvaal craton and is unique in that it is coeval with a world wide event of basic to ultrabasic submarine volcanicity associated with the Late Archean greenstone belts. Mineral deposits associated with pegmatites occur in the granitic terranes of the Rhodesian and Kaapvaal provinces and include tin, tungsten, tantalum, niobium, lithium, mica, and beryllium mineralization.

**Palaeoproterozoic**. Geological evolution of the Palaeoproterozoic (2.5-1.6 Ga) in Africa was marked by: repeated platform sedimentation and volcanicity; anorogenic magmatism originated as a result of tensional conditions subsequent to the stabilisation of the cratons or by combination of tectono-thermal events linked to accretionary processes; and development of accretionary and collisional orogens. Evolutionary changes in the Earth's atmosphere, hydrosphere, and biosphere took place during the Early Proterozoic and had a major influence on processes leading to metal accumulation. Intracratonic basins host important stratabound iron, manganese, asbestos, and copper mineralization.

TEnriched Superior-type iron formations occur in the northern Cape (e.g. Sishen), Transvaal (Thabazimbi), Angola (Cassinga), Mozambique (Honde), and Gabon (Belinga).

One of the first appearances of stratabound sedimentary copper mineralisation occurs at several stratigraphic levels within the thick sequence of early Proterozoic rocks of the Piriwiri-Lomagundi basin, northwestern Zimbabwe (e.g. Mangula, Shackleton,Alaska and Shamrocke).

Of great metallogenic importance are anorogenic basic-ultrabasic intrusions such as Great Dyke (Zimbabwe), Bushveld Complex (South Africa), Molopo (Botswana), Atchiza Complex ( Mozambique), and Kunene (Namibia-Angola). Some of these host economic deposits of chrome, PGE, iron, titanium, vanadium, and nickel/copper mineralisation.

Copper-rich Palabora carbonatite and the Premier diamondiferous kimberlite are probably both manifestations of extensional tectonic regimes prevalent within the thick stable Kaapvaal craton.

The 2.2-2.0 Ga Birimian terranes of West Africa represent a series of juvenile, accreted terranes. They consist of greenstone belts, which, like Archean greenstone belts, contain basaltic pillow lavas, andesitic to dacitic pyroclastic rocks and lavas, volcanogenic turbidites and manganiferous cherts, as well as flysch-type turbidites. All these rocks were metamorphosed to greenschist facies and intruded by peraluminous granitic plutons.

A great variety of mineralization occurs in Birimian greenstone belts, especially gold, manganese, iron, and also small but economic sulphide mineralization including lead, copper, antimony, silver, nickel and cobalt, and tin and tungsten. The following genetic types of gold mineralisation have been recognized: mesothermal lode, tourmalinized turbidite sandstone, quartz veins with native gold, shear-zone-hosted vein, intrusive disseminated, and porphyry copper-gold.

Collisional mobile belts such as the Ubendian-Rusizian (1.8 - 2.0 Ga) and Toro of eastern Africa are generally poorly mineralized. A stratiform syngenetic copper-cobalt deposit occurs at Kilembe in the Toro Supergroup. Hydrothermal lead, copper, and gold mineralization occur in Tanzania and are related to late-orogenic Ubendian igneous activity.

**Mesoproterozoic**. The Mesoproterozoic (1.6 Ga-950 Ma) is marked by one of the most distinctive orogenic events in Africa known as the Kibaran orogeny (1400-950 Ma). It includes the Kibaran, Irumide, southern part of Mozambican, and Namaqua-Natal belts. In this region, a series of rifting, sedimentation, magmatism, metamorphism, and deformation took place. The cross-cutting nature of the Kibaran belt with the Ubendian-Rusizian belt and the fact that it is also flanked by Archean massifs to the east and west supports the contention that the Kibaran belt developed intracratonically.

Mineralization within the different parts of the Kibaran belt differs markedly. The intracratonic Kibaran belt of central Africa, for instance, defines a major tin (-tungsten) province (northern Zaire, Burundi, Rwanda). Tin and tungsten tend to occur in quartz veins associated with late orogenic granitic intrusions. Beryllium, columbo-tantalite, and lithium ores occur in pegmatite zones close to but separated from the hydrothermal tin-tungsten mineralisation.

The Kibaran-age Irumide belt defines a somewhat indistinct copper province extending discontinuously from the Ghanzi region of northwestern Botswana to Klein Aub in Namibia. Within this belt, extensive sedimentary copper mineralisation occurs in a rift-bounded succession of mainly clastic sedimentary rocks.

Sedimentary exhalative massive sulphide mineralisation (copper, lead-zinc, silver) occurs in Namaqualand (Aggeneys, Broken Hill, Gamsberg).

Exhalative base-metal deposits of volcanogenic type occur in a long north-south trending belt adjacent to the western margin of the Kaapvaal craton. The Prieska copper-zinc mine, like the other deposits in the belt, is stratabound to a basic metavolcanic unit comprised mainly of amphibolites and amphibole gneisses.

**Neoproterozoic**. The Pan African Neoproterozoic tectono-thermal event affected much of Africa in the period from at least 950 Ma to about 450 Ma and led to the structural differentiation of Africa into cratons and orogenic belts. The Pan-African belts developed through a complex sequence of initial rifting phase with related sedimentation and magmatism, followed by ocean opening, subduction and plate collision and post-collision magmatism. The Katangan belt (Zambia and Zaire) forms a broad curved zone of deformed sedimentary rocks known as the Lufilian Arc. It hosts the major copper(-cobalt) deposits that are confined to specific shale or conglomeratic horizons within which may be a rift-bounded sedimentary succession. Apart from copper (-cobalt) deposits other significant deposits in the Copperbelt contain uranium-gold (Shink-olobwe, Zaire) and lead-zinc-copper-cadmium (Kipushi, Zaire).

The Matchless Amphibolite belt of the Damaran orogen in Namibia is closely associated with a number of volcanogenic exhalative massive sulphide deposits. The Otjihase and Matchless cupriferous pyrite bodies are the two most important deposits of this group. Similar mineralisation also occurs in the rocks of the coastal arm of the Damaran orogen in the Gariep belt of southern Namibia as exemplified by the Rosh Pinah zinc, lead, copper deposit.

Carbonate-hosted ( Mississippi-Valley type) base-metal mineralisation is well developed to the north of the central mobile zone of the Damaran belt in partially equivalent shelf or miogeosynclinal facies rocks (Tsumeb, Kombat, Berg Aukas).

Mineralisation associated with highly fractionated post-tectonic Damaran granites in the central Damaran belt includes tin, pegmatite-suite minerals, uranium, and gold. Small deposits of beryl, pollucite, columbo-tantalite, lepidolite, and related minerals occur in zoned pegmatites, particularly in the Karibib area, and are concentrated in a series of northeast-trending linear zones. The so-called "tin belts" are related to four of these zones, the most northerly of which contains the economically important Vis tin-bearing pegmatite deposit. Recently discovered gold-bearing skarn-type mineralisation occurs at Navachab near Karibib. The metamorphogenic Rössing uranium deposit near Swakopmund is the largest of its type in the world.

The Arabian-Nubian Shield contains an assemblage of accreted island arcs that formed in about 310 Ma. The Shield comprises juvenile crust that formed through the following tectonic stages: rifting, formation of ocean floor and arcs, collision and post-collisional tectonics. The volcano-sedimentary terranes of arc derivation host hydrothermal gold-quartz and gold-carbonate vein-type mineralisation in Ethiopia (e.g. Lega Dembi, Adola Greenstone Belt) and Eritrea (Gash-Setit Goldfield). Volcanogenic massive sulphides (Cu, Pb, Zn, Ag, Au), stratabound sulphide deposits, and sedimentary exhalative sulphide deposits are also present. Disrupted ophiolites of Arabian-Nubian Shield occur in linear belts up to 900 km long and sporadically contain stratabound nickel-sulphide deposits. Chromium mineralisation occurs as podiform ore bodies in ultramafic host rocks in Sudan. Tantalum-niobium mineralisation is commonly found in late tectonic alkali granites and/or pegmatites, whilst tin-tungsten mineralisation is related to late tectonic greissenised and albitised alkali granites.

The Mozambique belt (ca. 660Ma), which can be traced over 4000km along the entire eastern side of the African continent, is, like the Zambesi belt, a result of Pan-African rejuvenation of older rocks. High grades of metamorphism are characteristic of the belt. It hosts numerous pegmatite-associated deposits including those of: rare earths, tantalum, niobium, beryllium, mica and emerald.

**Assessment of undiscovered resources**

Undiscovered resources are likely to be identified in situations where:

- The terrain remains poorly explored. Africa is one of the last frontiers and has a large potential in this regard, for instance, in the cratonic environments of central and western Africa.

- Potentially mineralised terrain is overlain by unmineralised tracts of land, i.e. the Kalahari and Karoo basins of southern and central Africa.

- The metallogenic environment is conducive for large, hidden ore deposits to be located. The CGMW's project on exceptionally large deposits is aimed at this target.

A great deal of diligent work remains to be done to expand our knowledge by continued observation and documentation, and by adding value through the integration of relevant data, particularly geophysical, and the application of advanced data modelling techniques. Metallogenic maps also are indispensable tools to this end.

# Economics, ecology, and sustainable development of mineral resources in Siberia

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Siberia is considered one of the major regions on the globe where mineral resources will be responsible next century for industrial development not only in Russia but in many other countries of the world, particularly in Europe and the Asia-Pacific area. The richest in the world, explored and potential reserves of energy raw material (gas, oil, coal, gas hydrates), as well as nickel, cobalt, platinum-group metals, diamonds, rare-earth elements, helium, minerals used in agriculture, and many other kinds of mineral resources are concentrated in northern and eastern Siberia. Because of growing deficiencies of fresh water, the great reserves in Siberian rivers and lakes are of tremendous importance for the future progress of mankind. Lake Baikal alone contains 20% of world reserves of surface water (excluding water in glaciers in Antarctica and Greenland).

At the same time, Siberia, in contrast, has a combination of favourable and unfavourable nature-climatic, social-demographic, resource, and industrial factors that are unique in the world. Ecological, economic, social, and political problems are pronounced and were on the agenda of the XXI century in the schedule of the conference held in Rio de Janeiro in 1992. The acuity of ecological problems is defined by the fact that most of the large territory of Siberia (about 10 million square kilometers) lies in extreme climatic conditions, under which ecosystems are highly sensitive to anthropogenic loads, particularly in the areas of permafrost where major extractable and promising resources are concentrated.

Economic problems are defined on the one hand by the rich natural resources of Siberia and, correspondingly, by the great importance and weight of the mining and petroleum industries; and on the other hand, by the unfavourable natural and climatic conditions of their locations, poorly developed infrastructure and communication systems, and also by unbalanced mining and processing branches of industry, which in general decreases significantly their profitability and require large initial capital investments for putting new fields into production.

Social problems are to a large extent the consequence of the former two factors (natural-climatic and economical), and also of the historical social disparity between the Siberian and European parts of Russia, which is responsible for unfavourable demographic tendencies in the region. Social and economic problems in northern and eastern parts of Siberia are complicated by the fact that these require expensive measures for protection and preservation of natural environments and for aboriginal populations with their specific genetic adaptation to the extreme natural conditions.

Balanced and ecologically safe development of industry in Siberia, particularly as regards the petroleum and mining industries, is of political importance for present-day Russia and for its prospects nationally and globally. Mineral resources of this region comprise much of the raw-materials base of Russia's economy and its export potential, especially in energy fuels.

All of these problems become highly acute in connection with the transition of Russia from a command-administrative to a market economy, and with system crises that occurred as a result of some strategic mistakes. The following critical ecological and economic needs related to the development of mineral resources in Siberia are important to the future of our globe as the habitat of humanity:

- The need to reduce methane emissions to the atmosphere during the development and transporting gas, oil, and coal. At present, the methane content in the troposphere increases each year by 1-2%. About 1/3 of this increase in Siberia is attributable to the petroleum and coal-mining industries.

- The need for development and use of new ecologically clean technologies in the production and processing of raw materials. Such technologies are needed to process the huge spoil heaps from mining, which release some of the most dangerous impurities into the environment.

- The need to guarantee ecological safety to the territories related to the production of mineral resources, including those areas possessing a special status of Global Heritage, and, in Siberia, Lake Baikal and its surroundings are assigned to this category.

- The need for ecological monitoring and scientific substantiation of prospective scenarios for changes in the environment, accentuating the northern areas of Siberia where in connection with global rise in temperature there exists the threat of degradation of permafrost, which poses threats for the petroleum industry and the social infrastructure. In the light of these needs, we see the main tasks of modern geology not only in providing mankind with mineral resources, but also in helping developing new attitudes for their rational application.

The paper includes data on actual and potential reserves and locations of major kinds of mineral resources.

# Mineral supply and demand into the 21$^{st}$ century

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World population is growing faster than at any time in history, and mineral consumption is growing faster than population as more consumers enter the market for minerals and as the global standard of living increases. Does this mean that we will face a mineral supply crisis in the 21$^{st}$ century? If so, will this require increased mineral exploration along with the need for more geological information and better land access that this entails? To answer these questions, we need predictions of world demand for minerals into the 21$^{st}$ century and a better understanding of the relation between global mineral reserves and those in individual deposits.

World mineral demand will be affected by three general factors: uses for mineral commodities, population, and standard of living. Use of mineral commodities in the pure state is giving way to their inclusion in composite materials with better properties for many applications. It is impossible to foresee all of these new mineral products and the degree to which they will affect demand for individual mineral commodities. Regardless of specific uses, however, minerals will have to remain an important basis for world manufacturing and agriculture because there is no other material to replace them. Thus, changing uses will have local effects but are not likely to change the global mineral demand equation within the next 50 years or so.

Population will have a bigger effect on future mineral demand. Projections of future population range widely, depending on estimated fertility rates. For low fertility rates of 1.5 to 1.6 children per female, which are below the "replacement rate" of 2.1, world population is projected to increase to about 7 billion people (current population is about 6 billion) and to decline after that, reaching the 1950's level of 2.5 billion in about 2150. If, on the other hand, global fertility rates remain at 2.5 to 2.6, world population will reach about 25 billion in 2150. For the period 2000 to 2050, these two extremes would yield world populations of 7 or 10 billion, largely because population changes related to low fertility rates will not yet have begun to decline. The difference in these two population estimates for 2050 is not likely to result in mineral demand that differs by the same amount because there is a generally negative relation between per capita mineral demand and population for most countries. For instance, China and India have per capita copper consumption of 0.6 and 2.7 pounds per person respectively, whereas South Korea and Taiwan, with significantly smaller populations have per capita copper consumption of 29.2 and 66.7 pounds, respectively. This relation reflects the greater difficulty of raising the standard of living of large populations compared to small populations, as is well illustrated by Singapore. Because most future population growth will result from increases in developing countries where standard of living is low, the effect of higher populations on total mineral consumption will not be great, at least within the range of present estimates through 2050. Taking a middle estimate of about 8.5 billion for global population in 2050, and assuming that each additional person will demand slightly less than the one before them, suggests that increasing population will increase mineral demand by about 25% between 2000 and 2050.

Variations in standard of living could affect future mineral demand more than population. Per capita consumption of minerals has increased in almost all areas during the last century, with the biggest differences and changes related to increased standard of living. Asian developing countries have shown particularly impressive growth over the last few decades. Growth of per capita copper consumption in this area ranges from a low of about 40% in India to a high of about 82% in Taiwan between only 1985 and 1998. Changes in per capita copper consumption in most developed countries has been smaller, but have been positive in most cases. For the entire world, there has been an overall increase in per capita copper consumption of about 11% between 1985 and 1998, and 13% over the period 1971 to 1998, or about 0.5% per year.

These rough comparisons based on copper suggest that mineral demand could increase by about 1% per year between 2000 and 2050, with equal contributions from increasing population and improved standard of living. Economic cycles, recycling and other factors are likely to be second-order controls on overall demand for new minerals. Although per capita mineral consumption does vary with economic cycles, the trend toward gradually increasing global demand has been clear for many decades and is likely to remain in place. Thus, regardless of exact demand, it is almost certain to be higher than it is today, even if population does not increase. Some of the increased demand caused by population increase will be met by more effective recycling, but this can be applied only to some commodities and cannot meet overall demand as long as both population and standard of living increase. These comparisons indicate that increases in demand for minerals are almost inevitable for the next 50 years or so unless there is a major breakdown in global economic activity.

Global mineral reserves are adequate to supply this demand, at least in theory. Presently estimated global mineral reserves are 20 to almost 1000 times larger than present annual production, depending on the commodity of interest. If mineral demand increases at a 1% annual rate, as estimated above, it will be about 60% higher than today by 2050, which does not change the life of these reserves very much. Thus, demand is likely to remain the dominant factor in world mineral supplies for the next few decades. Exactly when supply will become the dominant factor is difficult to predict and will undoubtedly vary from commodity to commodity. In fact, the failure of earlier predictions of this type, many of which foresaw mineral shortages by the year 2000, has led to a dangerous complacency about future world mineral supplies.

Although mineral reserves are large and seem adequate for the next 50 years or so when considered as a single global number, geologic, engineering, economic, environmental and political factors require that reserves be re-evaluated on a continuing basis. Geologic factors are of first order importance, and can range from new discoveries to changes in mining, beneficiation, smelting or other treatment processes. Discoveries are the most important stimulus to exploration because they provide a reason to explore areas or geologic environments that were considered previously to be without potential. For example, discovery of the Olympic Dam copper deposit resulted in recognition of a new type of copper deposit, which has now been found throughout the world. On a smaller scale, deep drilling in the Carlin, Nevada (USA), area showed that gold ores originally considered to be near surface actually extend to significant depth, resulting in discovery of large new reserves. Geologic and engineering factors can combine to change mineral reserves. For example, introduction of heap leaching methods during the 1970's and early 1980's permitted mining of much lower grade gold ores; similar changes affected the copper industry, making oxide copper deposits economically attractive. The interim result of this has been gold and copper reserves in 2000 that differ greatly from those of 1970. These changes were not simply adjustments on paper. Instead, they involved discovery of many new deposits in an unusually successful period of global mineral exploration.

Political, economic, and environmental factors are also important and can be related. For example, initiatives to ban the use of cyanide, which have been put forward in several areas, could remove large volumes of gold-bearing rock from our current reserve. This could, in turn, place an emphasis on ores that are amenable to other forms of treatment, possibly even low-grade placer deposits. Similarly, initiatives to ban surface mining could change the form of ore bodies that are considered attractive for mining, putting a premium on those that can be mined by underground methods despite their higher operating costs. Changes in the political and economic landscape, such as the opening of most Latin American countries to outside mineral investment, have had an enormous impact on mineral exploration and reserves. Anticipated increases from other parts of the world have not been as great, in part because of less hospitable economic and regulatory climates.

The key point is that global mineral reserves are a dynamic response to changing factors throughout the world. Because of their pivotal role in world trade, land-use, and environmental decisions they must be reviewed constantly, but on the ground and in compilations. From a geologic perspective, the most important things that can be done to assure that world mineral reserve data meet the challenge of the new century are:

1) research into the nature of known processes that form mineral deposits with the goal of increasing our ability to recognize far-field indicators of mineralization and, hopefully, finding totally new ore-forming environments;

2) geologic mapping, related geochemical and geophysical surveys, and compilations of data on known deposits, prospects, and favorable geologic environments, to provide critically important background data on the surface and near-surface part of our planet to guide future exploration; and

3) drilling and other subsurface sampling, hopefully through a regulatory system that recognizes that discoveries can only be made by actually sampling new mineral deposits.

These actions will be essential if we are to be good stewards of Earth's mineral endowment and if demand is to continue to rule the global mineral supply-demand equation. As we enter a century that will be marked by greater world trade, they must be done at the scale of continents and even the entire Earth rather than individual countries, as has been the practice up to the present.

# The Mineral Databases of the U. S. Geological Survey

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The U. S. Geological Survey (USGS) has two mineral-resource databases, the Mineral Resources Data System (MRDS) and the Minerals Availability System (MAS). MRDS was built and maintained from about 1969 by the USGS and MAS was built and maintained by the U. S. Bureau of Mines from about 1970 until the bureau was eliminated by the U. S. Congress in 1996. The MAS database function was transferred to the USGS in that year. Although the two databases served different purposes, they also shared similar information, such as name, location, commodities present, and much other data. Soon after the USGS acquired the MAS database, a decision was made to merge MAS and MRDS. This will, however, take a large effort because in combination there are over 330,000 entries and about 250 available fields, with many duplicate entries between them. As a first step, we are placing the databases in a single data structure in an Oracle format.

In most studies involving mineral deposits, the first questions asked are: Where are the known deposits? What are the commodities? What are their host rocks? What minerals do they contain? These questions are asked whether the study is oriented toward exploration, assessment, or the environmental aspects of mineral deposits. When mineral deposit locations are plotted on maps showing geology, geochemistry, geophysical features, and exploration history, mineral database information is invaluable for mineral-resource assessments.

The USGS encountered many of the familiar issues one confronts when designing a new database structure. These issues will be discussed and include:

- Who are the primary users of the database?
- How will location information be stored?
- What scales are most important for the users of the database?
- Which fields should be mandatory?
- What is the proper or acceptable balance between rigidity and flexibility?
- What database platform is most appropriate?

Once the data in the two databases are transferred into the new structure, we will begin the task of merging their combined information. This will involve a commitment on the part of the USGS because it is multi-year effort that will be labor intensive, even in this era of abundant software tools.

# Global Mineral Exploration - Industry Perspective and Availability of Information

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The discovery of new mineral deposits requires innovative practical people, information, and places to explore. This triad defines the strategy and actions required for discovery and the need and use of information. Successful programs in new or poorly explored areas can be productive by applying both existing models and ideas and new ones. Well explored areas may require new ideas, better data, and innovative more-systematic exploration. While deposit models are the cornerstone in the initial application of available data, new ideas spring from the occasional unrestrained study of information.

While data sets and the GIS and statistical programs to manipulate these are ever more compatible, the availability and compatibility of data sets can be a restriction to their usefulness. Today there are more data available then ever before and the explorationist needs both access to and compatibility of a wide variety of information including, geologic maps; land, air, and space-based geophysical surveys; a wide variety of geochemical data; the ability to merge data; and the time to use it.

Therefore, governments and publicly (or mixed public/private) funded research institutions can provide an invaluable service to explorers by not only collecting, archiving, and indexing basic earth science data, but by making it readily accessible at low (or no) cost, especially in digital form. The latter should be in a format that allows for ready integration into exploration company databases, which are generally based on off-the-shelf software and hardware.

Today's minerals exploration environment is more competitive than ever. The financial returns of exploration dollars spent have diminished demonstrably over the last twenty years, and so has the number of companies actively exploring. Nonetheless, the surviving explorers are still well funded and increasingly technically sophisticated. What has increased are the number of "explorable" countries, i.e. those with political and economic risk profiles that are attractive to investment by international mining companies. The result is that there are more countries "chasing" fewer exploration dollars. Other than natural geological endowment, about which they can do very little, two competitive advantages countries can strive for are: making mining and tax codes more attractive to foreign investors, and improving the amount, quality, and accessibility of earth science data.

# Metallogenesis and tectonics as an integral part of The mineral resource assessment process

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## Introduction

A modern quantitative mineral resource assessment (QMRA) (Singer, 1993, 1994) employs interpretations of bedrock geology, tectonics, and mineral deposit genesis that are also employed in a modern metallogenic analysis (MA). A QMRA, as practised in various national and international projects of the U.S. Geological Survey (e.g., Pratt, 1981; Cox, 1993; Ludington and Cox, 1996), and a MA, as practised in recent international collaborative projects in the Russian Far East, Alaska, the Canadian Cordillera, and in Northeast Asia (Nokleberg and others 1995, 1997a, b, c, 1998a, b), utilize the following methodology: (1) defining key terms; (2) constructing a regional geologic base map that can be interpreted according to modern tectonic concepts and definitions; (3) compiling and synthesizing a series of mineral deposit models, utilizing modern tectonic definitions, that characterize the mineral deposits of the region; (4) systematically describing the mineral deposits so as to be able to determine mineral deposit models and origins; (5) delineating mineral resource tract (metallogenic belt) maps that contain a group of mines, deposits, prospects, and occurrences of a single mineral deposit type, or of related mineral deposit types that formed in a specific geologic (tectonic) event; (6) establishing a predictive character for undiscovered deposits by carefully defining each metallogenic belt to be the geologically favorable area for a group of coeval and genetically related mineral deposit types; and (7) interpreting the genesis of formation of bedrock geologic units and (or) structures, and of contained mineral resource tracts or metallogenic belts, using modern tectonic concepts.

However, a QMRA and a MA also employ different methods. (1) For a QMRA, an estimate of the number of undiscovered deposits for a particular mineral resource tract is made primarily by economic geologists familiar with the deposit types and with the help of a group of expert earth scientists (geologists, geophysicists, geochemists) who are knowledgeable about the geologic, tectonic, and metallogenic history of the region. And (2) for a MA (Figures 2, 3), an integrated metallogenic-tectonic model may be constructed using all available geologic, paleomagnetic, faunal, isotopic, and provenance data.

A QMRA, however, will greatly benefit from the formulation of a high-quality metallogenic-tectonic model (e.g., Figure 3) done in conjunction with the QMRA. For instance, suppose that a mineral resource tract containing porphyry Cu deposits is hosted in an island-arc terrane that now occurs in the center of a continent. Tectonic analysis of the origin of the island arc terrane, and possible correlation with other fragments of the island-arc terrane that may also contain the same metallogenic belt, should highly improve the quality of a QMRA. Because of these considerations, the successful completion of a classic, three-part QMRA (Figure 1) will greatly benefit from incorporating a modern metallogenic and tectonic model based on a detailed analysis and interpretation of bedrock geologic, geophysical, geochemical, and mineral resource data for the region of a mineral resource assessment.

**Defining Key Terms: Mineral Resource Tract and Metallogenic Belt**

Crucial to any systematic study are definitions of key or major terms. For a QMRA, a key term is a mineral resource tract, which is defined as an area permissive for the existence of deposits of one or more specified types and which are based on studies of known deposits within and outside the study area (Cox, 1993; Singer, 1993, 1994; Ludington and Cox, 1996). As discussed by Singer (1993), permissive boundaries are defined such that the probability of deposits of the type delineated occurring outside the boundary is negligible. For metallogenic analysis, a key term is a metallogenic belt, which is defined as a geologic unit (area) that either contains or is favorable for a group of coeval and genetically related, significant lode mineral deposit types (Nokleberg and others, 1997a, b, 1998b). Although somewhat different in wording, the two definitions share important features. Both a mineral resource tract and metallogenic belt: (1) are permissive for known or inferred mineral deposits of specific type or types; (2) can be irregular in shape and variable in size; (3) need not contain known deposits; and (4) are based on a geologic map as the primary source of information for identifying areas, and which delineate areas that are permissive for different deposit types.

**Construction of Regional Geologic Base Maps**

In order to define a mineral resource tract (or metallogenic belt) map, a regional geologic base map must be constructed that permits the display of a tract or belt as a function of the host rock geology and (or) host-rock structures (Pratt, 1981; Singer, 1993, 1994; Nokleberg and others, 1997a, b, c, 1998b). In order to facilitate interpretation of geologic relations and permit the estimation of undiscovered mineral deposits, the geologic base map must be constructed at the scale of the assessment and must show the major geologic data that can be related to the origin of the mineral deposits in each tract. Because mineral resource tracts and metallogenic belts are generally of large areal extent, interpretation of the tectonic origin of host-rock geologic units must be considered in order to display the geologic controls over formation of groups of mineral deposits in a specific mineral resource tract or metallogenic belt. Without interpretation of the origin (tectonic environment) of bedrock geology and structures, the interpretation of the origin of mineral resource tracts or metallogenic belts (and contained mineral deposits) will be a random process guided by no clearly established methods.

An example of a regional geologic base map is portrayed in Figure 2 that shows a simplified view of a terrane and overlap assemblage map of the Russian Far East. This map attempts to portray the major geologic features of the region that are essential for interpreting the geologic setting of selected major granitoid-related Au mineral deposits and their containing metallogenic belts. The figure portrays mid- and Late Cretaceous and early Tertiary continental margin arcs that constitute major overlap assemblages that host the granitoid-related Au metallogenic belt, and portray cratons, craton margins, and previously-accreted terranes.

**Compiling and Synthesizing Mineral Deposit Models**

Compiling and synthesizing a suite of mineral deposit models is essential to define the characteristics of specific mineral deposits, and to group the deposits into a finite number with similar characteristics. As an example, Table 1 shows selected major mineral deposit models defined and described for the metallogenic analysis of the Russian Far East, Alaska, and the Canadian Cordillera. A suite of 38 mineral deposit models is sufficient to describe the characteristic features of the 1079 lode deposits and placer districts of this large and complex region. Mineral deposit models, as classically described by Eckstrand (1984), Cox and Singer (1986), and Singer (1993), also permit synthesis of grade-tonnage models that are used to perform a QMRA.

**Table 1. Examples of selected major mineral deposit models and tectonic environments utilized for metallogenic analysis of Russian Far East, Alaska, and the Canadian Cordillera. Adapted from Cox and Singer (1986) and Nokleberg and others (1997a, b, 2000a).**

| Mineral Deposit Group | Mineral Deposit Model | Tectonic Environment |
|---|---|---|
| Deposits related to marine felsic to mafic extrusive rocks | kuroko Zn-Pb-Cu massive sulfide | Axial or back-arc region of island arc |
| | Besshi Cu-Zn massive sulfide | Oceanic rift |
| | Cyprus Cu-Zn-Ag massive sulfide | Oceanic rift |
| Deposits related to calc-alkaline and alkaline granitic intrusions | Polymetallic veins, Cu skarn, porphyry Cu, epithermal vein | Island-arc or continental-margin arc |
| | Porphyry Mo, Sn greisen and skarn, felsic plutonic U-REE | Continental-margin arc |
| Deposits related to mafic and ultramafic rocks | Zoned mafic-ultramafic Cr-PGE | Island arc |
| | Podiform Cr | Rift or island arc |
| Deposits related to regionally metamorphosed rocks | Au quartz vein, Cu-Ag quartz vein | Post-collision extension |

Inherent to constructing a mineral deposit model is the assignment of geologic (tectonic) environment(s) to models (Cox and Singer 1986, Singer, 1993). In a QMRA (e.g., Cox, 1998; Ludington and Cox, 1996), and in MA studies (Nokleberg and others, 1997a, b), a unique or small number of tectonic environments can be assigned to each mineral deposit model, as exemplified in Table 1. As another example, a detailed analysis for the lode deposits of the Russian Far East, Alaska, and the Canadian Cordillera reveals that only seven tectonic environments are needed to classify the origins of the 1079 lode deposits of this large and complex region (Nokleberg and others, 2000a): subduction-related arc, collisional (anatectic)-related arc, post-collisional extension, oceanic rift, continental rift, back-arc rift, and transform continental-margin arc.

## Description of Mineral Deposits

Part of the core data set for a QMRA and a MA is a high-quality description of the mineral deposits of the region. The descriptions need to systematically characterize the significant mineral deposits with sufficient detail so as to be able to determine mineral deposit model and origin, and provide tonnage and grade data if available (e.g. Ludington and Cox, 1996; Nokleberg and others, 1997a). The term significant mineral deposit is often employed, and is defined, for a specific mineral deposit model, as the mines, deposits, prospects, and occurrences that are judged to be important for a QMRA or MA (e.g., Nokleberg and others, 1997a). As an example of mineral deposit data for a MA, Table 2 provides sample descriptions of selected granitoid-related Au deposits for the Russian Far East.

**Delineating Mineral Resource Tracts and Metallogenic Belts**

Maps of mineral resource tracts (and metallogenic belts), along with underlying regional geology (e.g., terrane and overlap assemblage maps) constitute a basic element of the three-part methodology of a QMRA as described by Cox (1993) and Singer (1993, 1994). For delineation of mineral resource tracts or metallogenic belts, the following main principles are used (Nokleberg and others, 1995). (1) ***Mineral Deposit Association.*** Each mineral resource tract (or metallogenic belt) includes a single mineral deposit type or a group of coeval, closely-located and genetically-related mineral deposits types. (2) ***Tectonic Event for Formation of Mineral Deposits.*** Each mineral resource tract (or metallogenic belt) includes a group of coeval and genetically related mineral deposits that were formed as the result of a specific tectonic event (e.g., collision, accretion, rifting, etc.). (3) ***Favorable Geological Environment.*** Each mineral resource tract (or metallogenic belt) is underlain by a geological host rock and (or) structure that is favorable for a particular suite of mineral deposit types. (4) ***Geological or Tectonic Boundaries.*** Each mineral resource tract (or metallogenic belt) is usually bounded either by favorable stratigraphic or magmatic units, or by major faults (sutures) along which substantial translations have occurred. (5) ***Relation of Features of Metallogenic Belt to Host-Rock Units or Structures.*** The name, boundaries, and composition of each mineral resource tract (or metallogenic belt) corresponds to a suite of characteristics for the group of deposits and host rocks.

An example of a regional metallogenic belt map is portrayed in Figure 2, which shows selected, mid- and Late Cretaceous and early Tertiary major granitoid-related Au metallogenic belts for the Russian Far East (derived from Nokleberg and others, 1998b) superposed on a simplified terrane and overlap assemblage map of the region (derived from Nokleberg and others, 1997c). The figure illustrates the hosting of these metallogenic belts in mid- and Late Cretaceous and early Tertiary volcanic-plutonic belts that constitute major overlap assemblages that formed from continental margin arcs.

**Establishing a Predictive Character for Undiscovered Deposits**

With the above definition and principles, the area defined for a mineral resource tract or metallogenic belt, because it consists of a favorable geological environment and possesses a specific mineral deposit association, is predictive for undiscovered deposits. As an example, Figure 2 portrays the major granitoid-related Au metallogenic belts of Late Cretaceous and early Tertiary age in the Russian Far East. On the basis of regional geologic, geophysical, and geologic data, these belts are predictive for undiscovered mineral deposits of this type that formed in this specific geologic and tectonic environment (continental-margin arc) at this time (mid- and Late Cretaceous and early Tertiary). Because of these considerations, the synthesis and compilation of metallogenic belts is a powerful tool for mineral exploration, land-use planning, and environmental studies by a variety of governmental agencies, private companies and organizations, and university groups.

**Table 2. Examples of selected granitoid-related Au deposits for the Russian Far East. Adapted from Nokleberg and others (1997a).**

| **Deposit No.<br>Latitude<br>Longitude<br>Summary and References** | **Deposit Name<br>Metallogenic Belt** | **Major Metals<br>Minor Metals<br>Deposit Type** | **Grade and Tonnage** |
|---|---|---|---|
| | | | |
| K5310<br>42 52 18N<br>132 49 46E | Progress<br>Sergeevka | Au<br>Granitoid-related Au | Average grade of 5.89 g/t Au. |
| Consists of sulfide-poor pyrite-arsenopyrite-gold-quartz veins, small veinlets, poorly mineralized fracture zones, zones of mylonite, and zones altered to metasomatic carbonate-chlorite-sericite rocks. Deposit hosted in a Late Cretaceous granitic pluton that cuts a sequence of granitic-gabbro rocks of Sergeevka Complex with a Cambrian age of 500 to 527 Ma (J.N. Aleinikoff, written commun., 1992). The deposit is prospected to depths of a few tens m. This lode is also the source for nearby placer Au deposits.<br>A.N. Rodionov, written commun., 1991. | | | |
| | | | |
| N51-03<br>54 27 00N<br>124 14 00E | Kirovskoe<br>Stanovoy | Au<br>Granitoid-related Au | About 10 tonnes gold produced. |
| Consists of northwest-striking gold-quartz-sulfide veins hosted in an Early Cretaceous granodiorite stock. Veins commonly occur along contacts of diabase porphyry dikes that cut the granodiorite. Contacts of veins are generally sharp, although host rock is hydrothermally altered. Veins range from 0.5 to 1.0 m thick, and the surrounding altered rock ranges from 5.0 to 9.0 m thick. Altered rocks consist mainly of quartz, albite, sericite, and hydromica; the veins consists predominantly of 40 to 95% quartz. Main sulfides are pyrrhotite, arsenopyrite, and chalcopyrite, with less abundant galena, sphalerite, bismuthite, and tennantite-tetrahedrite. Gold ranges up to 0.28 mm diameter. Fineness of 844 to 977. Deposit source for the placer deposits of the Dzhalinda, Yannan, and Ingagli Rivers, the largest in the Russian Far East. Mined until 1961.<br>Gurov, 1969; G.P. Kovtonyuk, written commun., 1990. | | | |
| | | | |
| N52-02<br>53 27 00N<br>126 27 00E | Pioneer<br>North Bureya | Au<br>Granitoid-related Au | Average grade of 2.7 g/t Au, and 5.2 g/t Ag. Reserves of 17.1 tonnes Au, 20.1 tonnes Ag. |
| Consists of quartz, quartz-feldspar, quartz-tourmaline, and quartz-carbonate veins, and zones of altered quartz-potassium feldspar-sericite-albite rocks. Zones are 1 to 50 m thick, and in plan commonly branch and change trends. Ore zones are large, have low Au content and no visible boundaries. Extent of deposit determined by geochemical sampling. Gold and gold-sulfide ore assemblages are distinguished. Gold assemblage consists of quartz-adularia-carbonate veins; gold-sulfide assemblage consists of quartz veins with pyrite, galena, stibnite, and silver sulfosalts. Deposit hosted along margin of an Early Cretaceous granodiorite intrusion; both within the intrusion, and in adjacent contact metamorphosed Jurassic sandstone and siltstone.<br>N.E. Malyamin and V.E. Bochkareva, written commun., 1990; V.N. Akatkin, written commun., 1991. | | | |
| | | | |
| P55-35<br>61 27 32N<br>148 48 09E | Shkolnoe<br>Eastern Asia-Arctic, Verkhne-Kolyma zone | Au<br>Bi, Te, Ag<br>Granitoid-related Au | Total reserves 32 tonnes Au. Averages 29 g/t Au and 45 g/t Ag. Has produced 17 t Au and 17 t Ag since start of mining in 1991. Annual production of 3 t Au and 3 t Ag. |
| An en echelon system of quartz veins trending generally east-west. Veins occur in a multiphase granitoid stock about 4 km2 in size composed mainly of granodiorite and adamellite; that is intruded by dikes of granite porphyry, rhyolite, pegmatite, aplite, and lamprophyre. Quartz veins are surrounded by zones of beresitic and argillic alteration; skarn- and greisen-like alteration is locally present . Mineralization occurred in two stages separated by intrusion of lamprophyre dikes: (1) gold-polymetallic stage marked by molybdenite, arsenopyrite, loellingite, native bismuth, bismuth tellurides, and native gold; (2) the most economically important stage, marked by arsenopyrite, pyrite, polymetallic sulfides, gold, electrum, freibergite, tetrahedrite, lead-antimony and silver sulfosalts, argentite, and stibnite. Gold ore bodies extend to great depth.<br>Orlov and Epifanova, 1988; Voroshin and others, written commun., 1990; Palymsky and Palymskaya, 1990; Banin, 1993, written commun; Goncharov, 1995 | | | |

## Interpreting the Genesis of Bedrock Geologic Units and (or) Structures, Mineral Deposits, and Mineral Resource Tracts or Metallogenic Belts

By combining newly compiled data on geologic host rocks, structures, mineral deposit types, and metallogenic belts, a new, integrated interpretation can be constructed for the genesis of host rocks and mineral deposits. The new interpretation will strongly influence the quality of a QMRA and a MA. As an example, a comprehensive data base for the Russian Far East, Alaska, and the Canadian Cordillera (Nokleberg and others, 1997a, 1997b, 1997c, 1998b) consists of mineral deposit models, mineral deposit descriptions, mineral-resource tract maps, and terrane and overlap assemblage maps. Integration and interpretation of the data base produces a combined metallogenic-tectonic model (Nokleberg and others, 2000a, b; Scotese and others, 2000). One time stage of the model is illustrated in Figure 3 that illustrates the tectonic origin for major granitoid-related Au metallogenic belts in this region for the Late Cretaceous through early Eocene. In addition to depicting the major granitoid-related Au metallogenic belts, the figure also illustrates the configuration of cratons, craton margins, previously-accreted terranes, actively-migrating terranes, continental margin arcs forming major overlap assemblages, and oceanic ridges.

## Example of Methodology

The first parts of the methodology for a QMRA or MA is illustrated in Figure 4 (derived from Nokleberg and others, 1998a). Figure 4A illustrates a suite of metallogenic belts that are hosted in several geologic units, cratons, terranes, and overlap assemblages, or along major faults between terranes. Figure 4B, a series of stratigraphic columns for the units depicted in Figure 4A, illustrates the stratigraphic and metallogenic history of the map area. The steps in the methodology are as follows.

- Key terms are defined or cited from previous studies (e.g., Singer 1993, 1994; Nokleberg and others, 1997a).

- A regional geologic base map is constructed. Figure 4A, a map view of orogenic belts, illustrates two major cratons (A, B), several fault-bounded terranes (1, 2, 3, 4) between the two cratons, one accretionary assemblage (a), and four post-accretion overlap assemblages (b, c, d, e).

- A series of mineral deposit models are defined and described, and a high-quality mineral deposit data base is compiled (e.g., Table 2). For this theoretical example, the major mineral deposit models are low-sulfide Au quartz vein, ironstone, epithermal Au vein, porphyry Cu, bedded barite, and kuroko massive sulfide.

- Mineral resource tracts (metallogenic belts) are delineated. For this example, for simplicity, each tract (belt) contains only a single mineral deposit type, and tracts (belts) are not named. The two cratons (A, B) each contain distinctive, pre-accretionary metallogenic belts (ironstone and bedded barite deposits) that formed early in their geologic history, and (island arc) terrane 4 contains a pre-accretionary metallogenic belt of kuroko massive sulfide deposits. Between terranes 3 and 4 is accretionary assemblage a that contains a collisional granitic pluton with a porphyry Cu metallogenic belt that formed during accretion of terrane 3 against terrane 4. Between terranes 1 and 2 is a metallogenic belt containing Au quartz vein deposits that formed during accretion of terrane 1 against terrane 2. Overlying all terranes and both cratons is post-accretion overlap assemblage e containing a metallogenic belt with epithermal Au vein deposits.

- The genesis of formation of bedrock geologic units and (or) structures and contained mineral resource tract or metallogenic belt is interpreted using modern tectonic concepts (Figure 4B). Examples are: kuroko massive sulfide deposits forming in an island arc environment; porphyry Cu and low-sulfide Au quartz vein deposits forming in an accretionary environment, and epithermal Au vein deposits forming in a continental-margin igneous-arc environment.

- By carefully defining each mineral resource tract (metallogenic belt) to be the geologically favorable area for a group of coeval and genetically related mineral deposits, a predictive character is established within the tract (belt) for undiscovered deposits. The tracts (belts) will be valuable for mineral exploration, land-use planning, and environmental studies.

**Example of an Integrated Metallogenic-Tectonic Model**

For a MA, an integrated metallogenic-tectonic model may be constructed using all available geologic, paleomagnetic, faunal, and provenance data. In addition to providing basic insight into the formation of bedrock units and mineral deposits, the establishment of a well-defined metallogenic-tectonic model, done in conjunction with a QMRA, will feed back into, and increase the quality of a QMRA. For the region of the Russian Far East, Alaska, and the Canadian Cordillera, a dynamic metallogenic-tectonic model is constructed from a geologic, tectonic, and metallogenic analysis of the region (Nokleberg and others, 2000a, b; Scotese and others, 2000). As an example, Figure 3 depicts one time-stage of the metallogenic-tectonic model for the Late Cretaceous through early Tertiary. As another example of part of an integrated metallogenic-tectonic model, Table 3 summarizes the tectonic origins of selected major mineral deposit types for this region.

**Table 3. Summary of major tectonic origins for the metallogenic-tectonic model of the Russian Far East, Alaska, and the Canadian Cordillera. Adapted from Nokleberg and others (1997a, b, 1998b, 2000b).**

| Time | Areas | Tectonic Origin(s) | Major Mineral Deposit Types |
|---|---|---|---|
| Late Proterozoic, Late Devonian, Early Carboniferous | Northeast Asia and North American Craton Margin | Rifting | Sedimentary-exhalative Zn-Pb. |
| Late Triassic through mid-Cretaceous | Offshore of North Asia and North American Craton Margins | Island arc | Porphyry, epithermal vein, polymetallic vein, skarn. |
| Jurassic through mid-Cretaceous | North Asian and North American continental margins | Accretion | Low-sulfide Au quartz vein, granitoid-related Au. |
| Mid-Cretaceous through Present | North Asian and North American continental margins | Continental-margin arc | Porphyry, epithermal vein, polymetallic vein, skarn. |
| Late Jurassic through Early Cretaceous, Late Cretaceous through early Tertiary, and middle Tertiary | North Asian continental margin | Transform-continental margin faulting | Zoned mafic-ultramafic PGE, Cr, and Ti; W skarn, porphyry Cu-Mo, Au-Ag epithermal vein. |
| Late Cretaceous through Present | North America continental margin | Transform-continental margin faulting | Displacement of previously-formed metallogenic belts and host rocks. |

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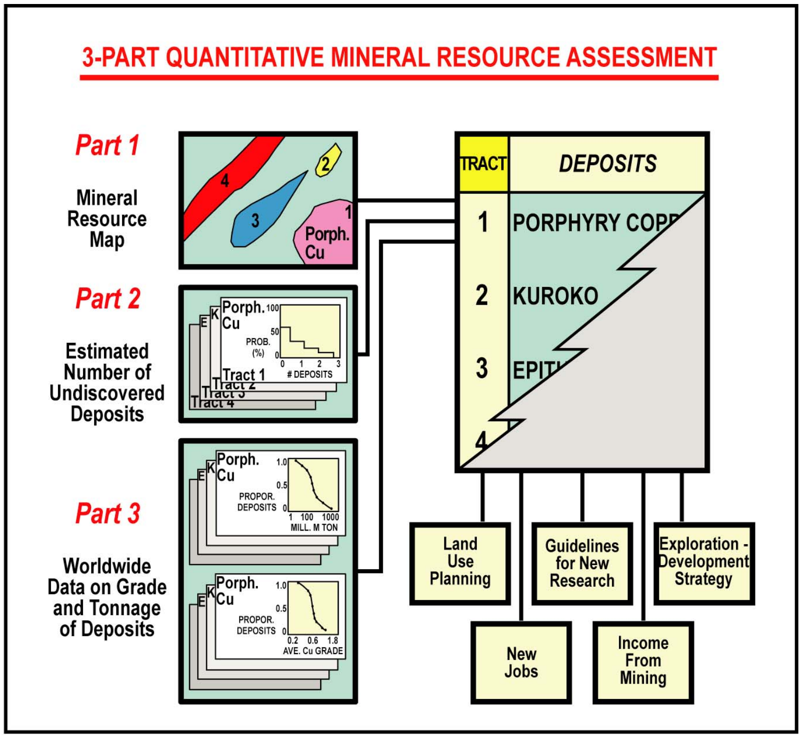


Figure 1. Majors parts of the 3-part quantitative mineral resource assessment. Adapted from Singer and Cox (1988) and Singer (1993).

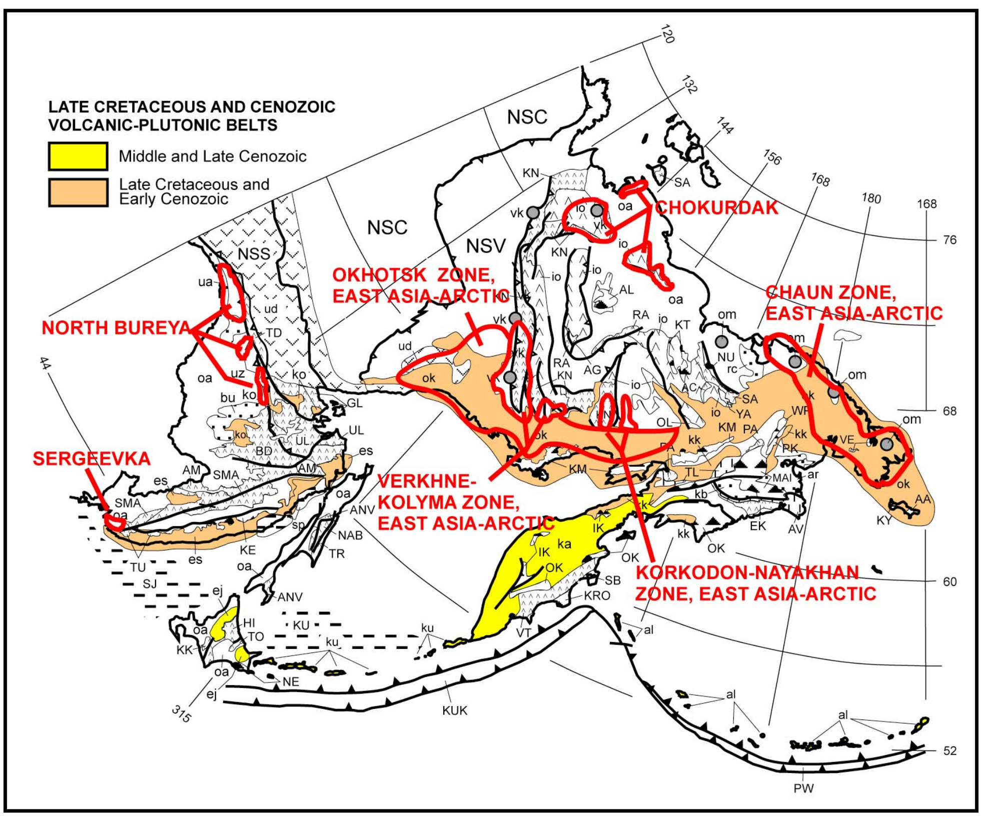


Figure 2. Regional geologic map showing major post-accretionary granitioid-related gold metallogenic belts in the Russian Far East. Adapted from Nokleberg and others (1997a, 1997b, 1988).

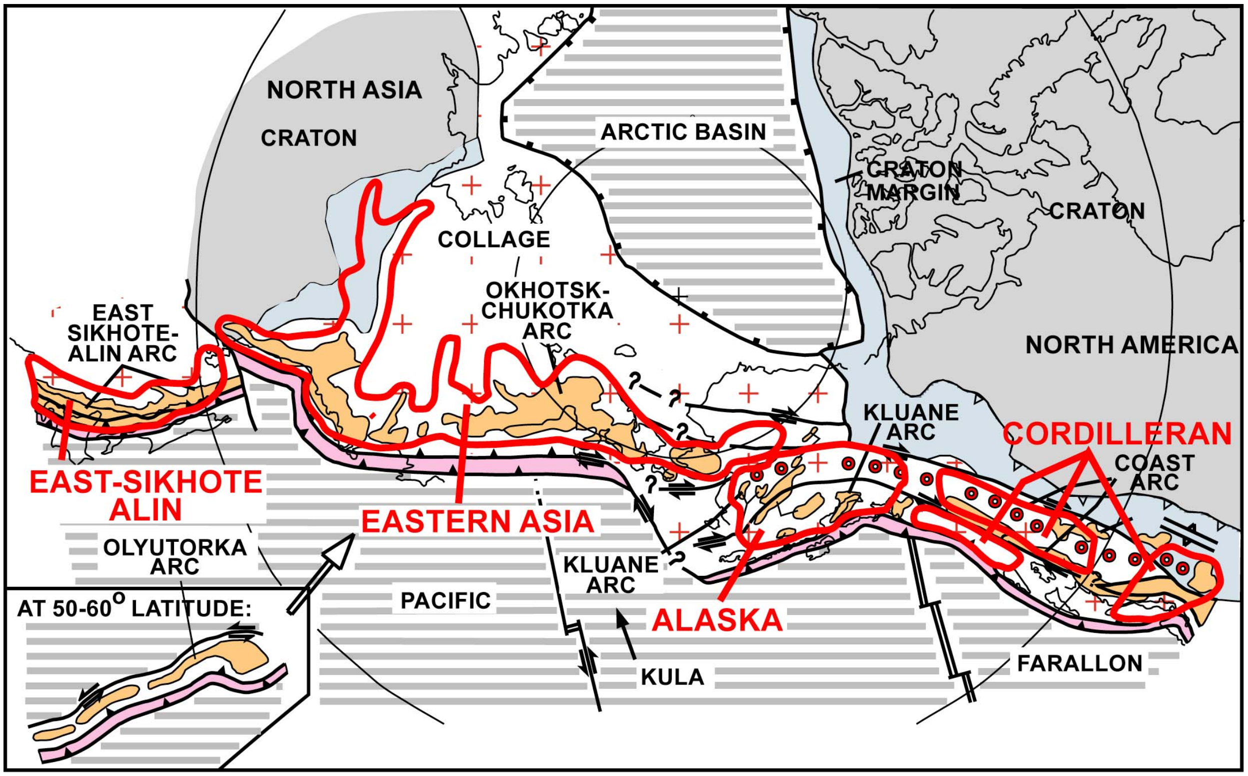


Figure 3. Late Cretaceous and early Tertiary stage of metallogenic and tectonic model illustrating tectonic setting for major granitoid-related gold metallogenic belts for the Russian Far East, Alaska, and the Canadian Cordillera. Adapted from Nokleberg and others (1988, 2000b).

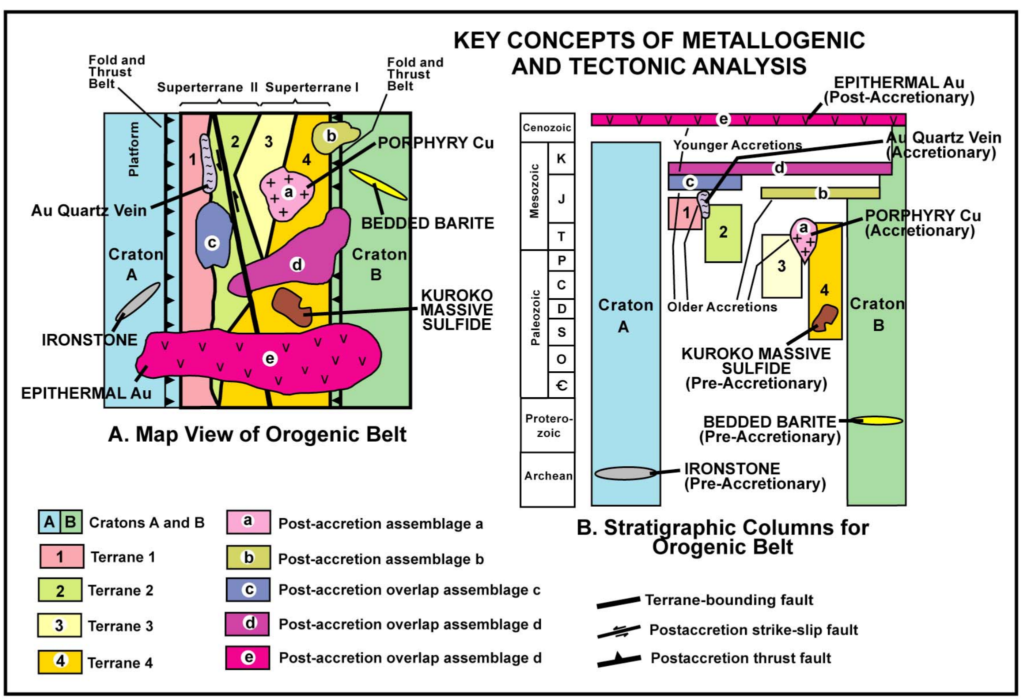


Figure 4. Generalized theoretical figure illustrating the methodology for metallogenic analysis of cratons, terranes, accretionary assemblages, overlap assemblages, and contained metallogenic belts. A. Map view of orogenic belt. B. Stratigraphic columns for orogenic belt. Adapted from Nokleberg and others (1988a). Refer to text for explanation

## Sustainable development and non-renewable resources— A multilateral perspective.

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The link between Sustainable Development and Non-renewable Resources appears at first glance to be inconsistent, because non-renewable resources are finite. The concept of sustainable development has generated a great deal of debate and spawned a multitude of definitions since it was put forward by Thomas Malthus nearly 200 years ago. He argued that the fixed land base could not sustain the continuing growth in the human population, and if people did not restrain their reproduction, the population would be controlled by war, pestilence, and starvation. This early thinking evolved to what we now accept as the fundamental premise of sustainable development as stated in the Brundtland report – development that meets the needs of the present without compromising the ability of future generations to meet their own needs. UNDP believes that development must have a human face and coined the term sustainable human development. Its mission therefore is to help countries in their efforts to achieve sustainable human development by assisting them to build their capacity to design and carry out development programmes in poverty eradication, employment creation and sustainable livelihoods, the empowerment of women, and the protection and regeneration of the environment, giving first priority to poverty eradication.

The idea of sustainable development in the context of non-renewable resources, in particular mineral resources, may be a contradiction if a one-dimensional view is taken. Mineral resource development is unsustainable only if we ignore the complex interaction of economic growth, social development, and the environment. It is not always self-evident that our present modern technological society requires an ongoing supply of minerals. Mineral production, although having environmental impacts, is and will continue to be an essential part of ensuring the economic well-being of our society. To satisfy the present global mineral needs without compromising the mineral resource needs of future generations, it is imperative that we approach mineral resource development within a holistic framework comprising all components of the complex interaction between humans and the ecosystems on which they depend. By using non-renewable resources for capital formation that will be reinvested in social, economic, and environmental activities, the concept of sustainability and mineral resource development would no longer seem to be a contradiction.

Since the establishment of the United Nations Development Programme (UNDP) in 1965, the organization has supported mineral resources development activities including exploration, feasibility studies, capacity building, and institutional strengthening of Mining departments in developing countries. Several mineral deposits were discovered, and one of the earliest and largest discoveries was the Baja la Alumbrera copper deposit in Argentina. Today, UNDP's direct involvement in the mineral sector is minimal, mainly because it is felt that this activity should be left to the private sector. However, the wealth of information that resides within its archives could contribute to the global assessment of future sources of mineral supplies. This is seen as a prerequisite to adequate planning for the sustainable use of these non-renewable resources and as a contribution to the achievement of UNDP's overarching goal of poverty eradication.

This paper discusses the evolution of the concept of sustainable development and the need to treat mineral resource development as one component in a complex interaction between humans and their environment. UNDP's approach and contribution to fostering an enabling environment for global mineral resource development within the framework of sustainable human development is presented.

# U.S. Geological Survey National Mineral Resource Assessment— An Estimate of Undiscovered Gold, Silver, Copper, Lead, Zinc Remaining in the United States

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The U.S. Geological Survey (USGS) conducted a 5-year scientific study to estimate in probabilistic terms, for the first time, the amounts of gold, silver, copper, lead, and zinc that could be present in yet-to-be discovered mineral deposits one kilometer or less below the surface of the United States. Results for the conterminous United States were published in 1996 (U.S. Geological Survey Minerals Team, 1996). Results for the entire United States, including Alaska, are in press (National Mineral Resource Assessment Team, in press). The National Assessment shows that it is likely that the United States still contains at least as much gold, silver, copper, lead, and zinc in conventional-type deposits as has already been discovered.

## Why Was a National Mineral-Resource Assessment Needed

The USGS undertook the National Mineral-Resource Assessment to provide timely, objective, credible mineral-resource information for land and resource planning and decision-making. As a Nation's economy matures, progressively greater attention is given to land use and environmental quality, as well as to sustainability of mineral supplies to provide for the needs of future generations. National mineral-resource assessments provide a framework for addressing these issues by monitoring the Nation's mineral wealth and by contributing to deliberations about resource extraction and protecting the environment. Responsible stewardship of the Nation's lands, resources, and environment requires information on where future mineral resources may exist, the amounts of a mineral commodity or commodities that these resources might contain, and what environmental impacts might result from extraction and development of such resources.

However, starting in the early 1990s, the tempo and politicization of land, resource, and environmental planning and decision-making in the United States began accelerating (again). An estimated 190 million acres of public lands, although lacking modern mineral assessments, was being proposed for withdrawal from access to mineral exploration, discovery, and production. This situation virtually assured that large deposits of undiscovered mineral resources would be withdrawn unknowingly and without consideration of alternative supplies.

For a number of reasons, detailed conventional large-scale mineral assessments were an impractical response to the burgeoning need for minerals information that accompanied the accelerating planning and decision-making process: (1) deadlines were too short and unpredictable to conduct new assessments targeted to specific areas under consideration for withdrawal; (2) locations of areas of concern were unpredictable and the areas under consideration were becoming much larger (up to 10's of millions of acres); and (3) the boundaries of these areas were uncertain.

Because of this growing unpredictability, it was recognized that what was needed was a nationwide mineral-assessment data base available in advance of the planning process for *all* areas of the country. However, the cost of providing such comprehensive data at traditional large, detailed scales was too high. For example, we estimated that collecting comprehensive mineral-resource data just for public and enclosed private lands at a scale of 1:250,000 would cost between \$2 and \$3 billion over a period of 15 years. Such a cost was too much and the time too long. The National Mineral Resource Assessment described herein was proposed and conducted as an alternative mechanism for developing, organizing, consolidating, augmenting, and maintaining large geological, geochemical, geophysical, and mineral-resource digital data bases capable of supporting mineral-resource and associated mineral-environmental assessments and research, at multiple scales and levels of detail throughout the country.

**How the Assessment Was Done**

The nature of available data and current technology, combined with limitations of time and money, dictated that the National Assessment be undertaken from a regional perspective. The country was divided into 19 geographic regions that were selected to provide broad geologic groupings of the Nation's mineral-producing areas. Each region was assessed by a scientific team composed of from 6 to 24 geologists, geochemists, geophysicists, and resource analysts knowledgeable of the region and its mineral deposits.

The method used to estimate the quantity and quality of undiscovered deposits of gold, silver, copper, lead, and zinc was the three-part quantitative assessment procedure (Singer, 1993) applied by the USGS increasingly since 1975. This procedure is based on mineral deposit models, which consist of sets of geoscience data that describe a group of deposits having similar geologic settings and distinctive grade and tonnage characteristics.

The first part of the three-part assessment is to prepare maps that identify and delineate tracts permissive for the occurrence of undiscovered deposits by deposit type (Figure 1). A permissive tract is defined by its geographic boundaries such that the probability of deposits of the type delineated occurring outside the boundary is negligible. Tracts for the National Assessment were delineated to allow estimates of undiscovered resources to be made to a depth of one kilometer below the surface where possible. Areas that were covered by more than one kilometer of rock known or inferred to be barren, were excluded from the assessment. Permissive tracts were delineated by interpreting and integrating existing geologic, geophysical, and geochemical data, and information available on known deposits in the area, all rendered onto maps at scales of 1:500,000 and 1:1,000,000.

The second part of the assessment method is estimating the number of undiscovered deposits of each deposit type in those permissive tracts where available information allows quantitative estimates. The number of undiscovered deposits is expressed as a probability distribution with estimates of the number of undiscovered deposits made at the $90^{th}$, $50^{th}$, and $10^{th}$ percentile confidence levels, and sometimes at the $5^{th}$ and $1^{st}$ levels (Figure 2). The estimates are made by subjective interpretation and extrapolation of available earth science information by geoscientists with detailed knowledge about the area and (or) the selected deposit type(s). The estimates of numbers of undiscovered deposits are constrained by the requirement that these deposits have grades and tonnages similar to the deposit model appropriate to the tract. In most cases, the models used in the National Assessment were those described by Cox and Singer (1986) and Bliss (1992).

The third part of the assessment method uses a Monte Carlo simulation computer program to combine the probability distribution of the number of undiscovered deposits with the grade and tonnage data sets associated with each deposit model to obtain the probability distribution for the undiscovered metal in each tract (Root and others, 1992, 1997). For the National Assessment, the resulting cumulative probability distributions represent the estimated quantities of gold, silver, copper, lead, and zinc in each tract, and allowed various fractals and the mean estimates to be obtained for the tracts (Figure 3).

## Results of the Assessment

In the National Assessment, 55 major deposit models and submodel types were used to delineate 447 permissive tracts. Quantitative estimates of undiscovered mineral resources were possible in 305 of these tracts (Light, 1998; Ludington and Cox, 1998). In addition to estimating gold, silver, copper, lead, and zinc in undiscovered mineral deposits, the National Assessment (National Mineral Resource Assessment Team, in press) also estimated resources of these metals remaining in, and produced from, identified deposits:

- In undiscovered deposits minable with existing technology—18,000 metric tons (t) of gold, 460,000 t of silver, 290,000 kilotons (kt) of copper, 85,000 kt lead, and 210,000 kt of zinc.

- In identified deposits—15,000 t of gold, 160,000 t of silver, 260,000 kt of copper, 51,000 kt of lead, and 55,000 kt of zinc.

- Past production from the largest identified deposits (accounting for about 99% of cumulative domestic production)—12,000 t of gold, 170,000 t of silver, 91,000 kt of copper, 41,000 kt of lead, and 44,000 kt of zinc.

## Some Implications

The USGS National Mineral Resource Assessment provides the first quantitative estimate of the amounts of undiscovered gold, silver, copper, lead, and zinc in the United States. The results suggest that for conventional-type deposits of these five metals, the United States still contains about as much in undiscovered deposits as was discovered previously.

Along with providing estimates of the quantity and quality of undiscovered mineral resources, the National Assessment provides a consistent, systematic data base of current geologic and mineral-resource information at a national scale. This data base permits, at least at some minimum level, evaluation of the impact of land-use decisions on the Nation's undiscovered mineral resources. Large parts of the areas delineated as permissive for occurrence of undiscovered deposits already are unavailable for future mineral exploration and development because of their use for urban, transportation, and other development, and their withdrawal for wilderness, scenic areas of various kinds, national parks and monuments, wildlife refuges, endangered species protection, and so on. The National Assessment data base provides Federal, State, and local land-management agencies information with which to estimate potential cumulative environmental impact of possible exploration and mining activities, to evaluate the potential economic benefits of mining in comparison with other land uses, to evaluate and plan for the potential impact of mining activities on other land uses, and to appraise the fair market value of land proposed for leasing, sale, exchange, or taking. The permissive tracts delineated as part of the National Assessment also permit industry to focus mineral-exploration programs on the areas and regions most promising for new discoveries.

National assessments conducted on a recurring basis can provide a means to help ensure adequate mineral supplies and effective stewardship of environmental and other resources in the future. The National Assessment methodology may serve as a guide for undertaking assessments at continental and global scales.

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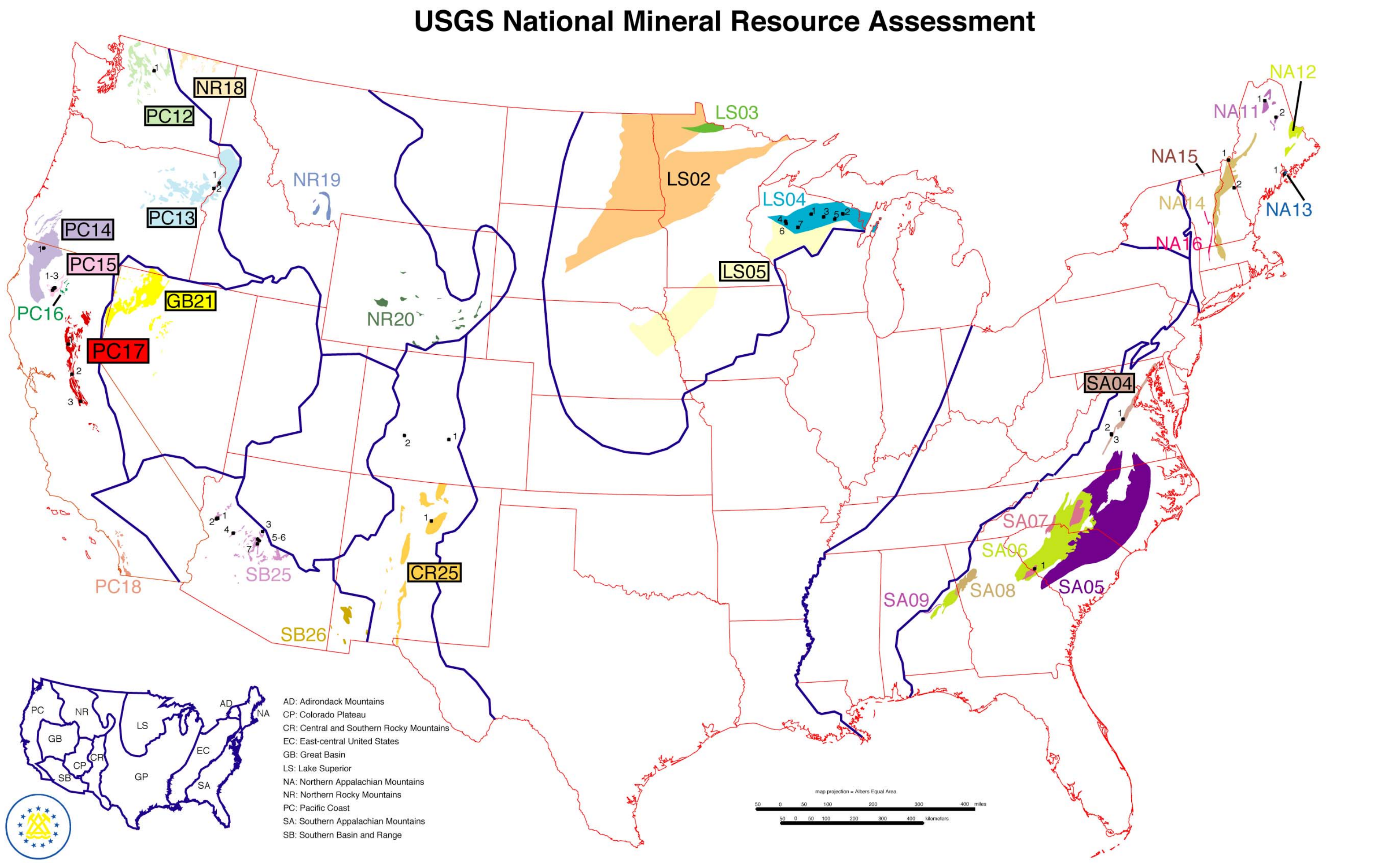


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Figure 1. Permissive tracts delineated for Kurko-type massive sulfide deposits in the conterminous United States

## Tract PC-17

### Massive sulfide, Sierran kuroko

There is a 90% or greater chance of 2 or more deposits.
There is a 50% or greater chance of 13 or more deposits.
There is a 10% or greater chance of 25 or more deposits.
There is a 5% or greater chance of 25 or more deposits.
There is a 1% or greater chance of 25 or more deposits.

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

| Quantile | Cu | Au | Zn | Ag | Pb | Rock |
|---|---|---|---|---|---|---|
| 0.95 | 700 | 0 | 0 | 0 | 0 | 97,000 |
| 0.90 | 12,000 | 0 | 12,000 | 18 | 0 | 690,000 |
| 0.50 | 140,000 | 16 | 260,000 | 710 | 46,000 | 8,500,000 |
| 0.10 | 310,000 | 45 | 815,000 | 2,700 | 200,000 | 19,000,000 |
| 0.05 | 360,000 | 55 | 990,000 | 3,400 | 250,000 | 22,000,000 |
| Mean | 160,000 | 20 | 340,000 | 1,100 | 76,000 | 9,200,000 |
| Probability of mean | 0.46 | 0.43 | 0.40 | 0.38 | 0.38 | 0.46 |
| Probability of zero | 0.04 | 0.06 | 0.06 | 0.05 | 0.10 | 0.04 |

Luddington, Steve, and Cox, D. P. (eds.), 1996, National Mineral Resource Assessment: USGS Open File Report 96-96 (CD-ROM)

Figure 2. Estimated number of undiscovered Kurko-type massive sulfide deposits in Tract PC-17.

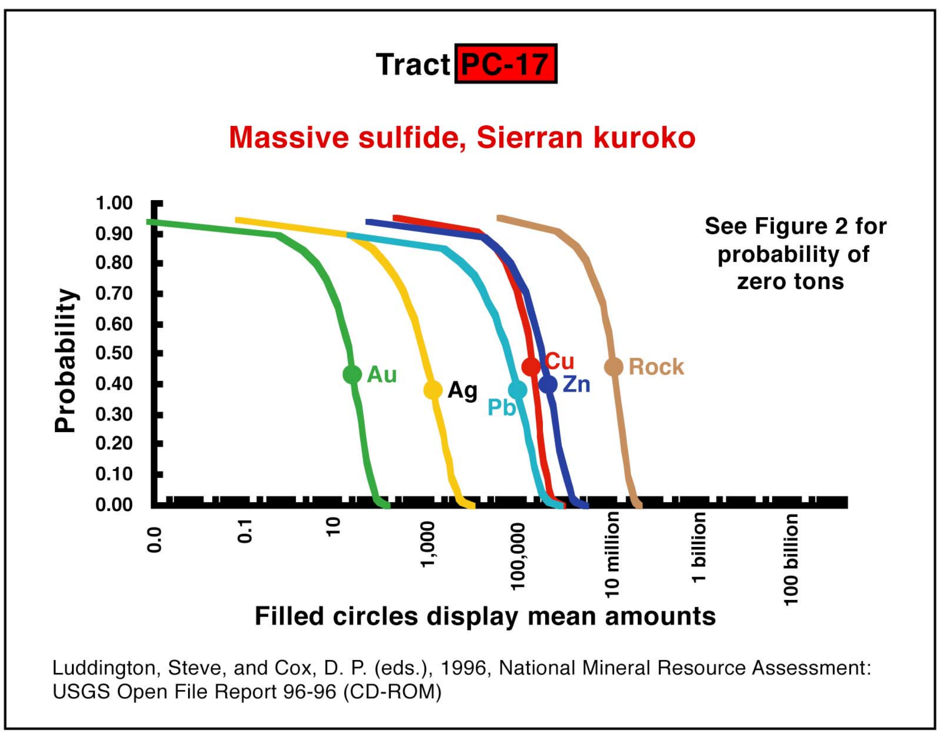


Figure 3. Cumulative distributions of contained metal and mineralized rock (metric tons) in Tract PC-17.

# The contributions of geologic information to economic, social, and environmental sustainability

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Environmental issues received increasing attention during the last three decades of the 20th century, a state that will no doubt continue as we enter the 21st century. Societies all over the world began to realize that the ability of the earth's systems to supply natural resources and services is finite, but that demands on those systems are rapidly multiplying (Arrow et al., 1995). The viability of current lifestyles and consumption patterns began to be questioned. Many different societies and professions embraced the paradigm of sustainable development as a philosophical construct within which to frame fundamental questions about the use and preservation of natural capital. The paradigm is based upon the ethical premise that current growth should not be achieved at the expense of future generations (WCED, 1987).

Sustainability deals with the inter- and intra-generational implications of finding an appropriate balance among the needs of economic, environmental, and social systems. While no single definition of sustainable development is acceptable to all parties, the general concept of sustainability has become so widespread in recent years that politicians and decision makers have embraced it as an underlying way of thinking about their programs and policies. Sustainability is often described in terms of principles, criteria, and indicators, where criteria represent statements of what is meant by principles of sustainability, and indicators are measures of the degree to which the criteria are being reached (Granholm et al., 1996). Because indicators require measures and measures must be supported by data, it follows that a focus on sustainable development will inevitably lead to an increase in the demand for reliable, unbiased information.

Science is "the organized systematic enterprise that gathers knowledge about the world and condenses the knowledge into testable laws and principles" (Wilson, 1998, p. 53). Given that science expands our understanding of the world, it is reasonable to expect that policy makers and the public will look to scientists for information about the status and functioning of the earth's systems. The current interest in issues of sustainability will thus help raise the visibility of both the social and natural sciences, including geology. To the degree that scientists are willing and able to address the urgent needs of society, and then communicate their knowledge to the public and decision makers, the status of the sciences will be improved as well (Lubchenco, 1998).

In this presentation, I will discuss one facet of the complex interaction between experts and the public, how to increase the likelihood that the scientific expertise of geologists, and the data they can provide, are utilized in the development and review of policies related to sustainable development.

The field of geology developed largely in response to societal needs for natural resources, particularly energy and mineral resources, and also in part because of geo-genic impacts on human-made environment. Energy and mineral resources remain integral components of economic and social systems, providing essential inputs to virtually every economic sector, and acting as the driving force for some local, regional, and national economies. At the same time, resource extraction, processing, use, and disposal can have serious environmental consequences that have the potential to threaten environmental security and degrade present and future quality of life (Shields, 1998). In addition, surface and near-surface earth (geological) processes determine both the character of the landscape and the state of the physical and built environment (Hughes, 1995; Berger and Iams, 1996). Clearly, geologic information will be relevant to many aspects of sustainable development.

Geologists have traditionally focused on the scientific and technical aspects of their field; but if they are to be perceived as relevant to the sustainability debate, they will have to demonstrate that geologic information will help societies achieve the goal of sustainable socio-economic and biophysical systems. Being conversant will the concept of sustainability will be necessary, but not sufficient. Geologists will need to understand the policy making process and enhance their communications skills so that they are able to present geologic information in a format that is understandable, and at a point in the policy or management cycle that is useful to decision makers. Another important step in getting geologic input utilized will be to reach a mutual understanding between the data user and data provider about the ultimate purpose for those data. The geologist, in the role of data provider, has to be aware of needs of the data user and vice versa. The data user has to be aware of the limitations of the data provided. This suggests that the range of information that geologists will need to supply should go well beyond what has traditionally been the case.

As Lubchenco (1995) points out, the best policy is based on the best science. Science, however, is a dynamic, ongoing process that is continually discovering new information. Thus, the interaction between science and policy must also be ongoing and dynamic. She lists eight types of useful scientific communication: what is known; the certainty with which it is known; what is not known; what is suspected; the limits of science; probable outcomes of different policy options; key areas where new information is needed; and recommended mechanisms for obtaining high-priority information.

Essentially, Lubchenco is recommending a proactive role for scientists, one in which they provide not just information, but also frame the issues, set research priorities, synthesize complex information, and perhaps most important, communicate how science works. This expanded role is an appropriate one for geologists.

Policy making is a cyclical process that progresses through a series of stages. We propose a model the comprises 6 stages: (1) identification of objectives and interests, (2) definition of policy, (3) codification of policy in laws and acts, (4) establishment of a regulatory framework, (5) monitoring, and (6) review and adaptation. The type of input geologists provide will depend upon where a society is in this policy cycle and also on the decision context, be it in the mineral sector, an issue related to land use and development, nature conservation, or interactions between the environment and society, i.e., anthropogenic versus geogenic impacts.

Clearly there is a need for input from geology as a country's mineral policy is being defined. The consensus building process necessary to the achievement of a relevant and widely accepted mineral policy will depend in part upon information about the impacts and consequences of choosing one policy option over another. Decision makers will need information about the depletion of mineral resources and the environmental effects of mining. For earth scientists the challenge will be to develop: (1) a better scientific basis for discussion of adequacy of minerals resources; (2) better data on factors involved in mineral supply that should be in public-policy analysis and decisionmaking; (3) better ways to communicate to policymakers and the public the dynamic nature of mineral supply, thus putting the prospect of "running out" in the proper context; and (4) methods to incorporate recycling and reuse into the concept of sustainability (Committee on Earth Resources, 1997).

There is also an enormous need for science input in the development of laws and regulations regarding the environmental impacts of mining. There is a high cost to society when the government enforces laws and subsequent regulations that make no sense to people (Wilson and Anderson, 1997). Here, geologists can provide information about: (1) the environmental consequences of mining, including the costs of environmental compliance and the effects of using best practices in the environmental management of mining; (2) improved environmental management and restoration ecology associated with mining and mineral processing; and (3) information to policymakers and public about how mining affects the environment and how environmental degradation can be minimized (Committee on Earth Resources, 1997).

Finally, the input of science in the review and adaptation phase cannot be under estimated (Figure 2). Environmental regulation will not quickly adapt to scientific advances unless scientists themselves remain involved in the policy cycle. However, given the engagement of scientists and a societal willingness to respond to new information and changing preferences, adaptive management is possible (Lee, 1993).

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**Deposit models and their application in mineral resource assessments**

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Mineral deposit models are important in quantitative resource assessments for two reasons: (1) grades and tonnages of most deposit types are significantly different, and (2) types occur in different geologic settings that can be identified from geologic maps. Mineral deposit models are the keystone in combining the diverse geoscience information on geology, mineral occurrences, geophysics, and geochemistry used in resource assessments and mineral exploration. Far too few thoroughly explored mineral deposits are available in most local areas for reliable identification of the important geoscience variables or for robust estimation of undiscovered deposits—thus we need mineral-deposit models. Well-designed and -constructed deposit models allow geologists to know from observed geologic environments the possible mineral deposit types that might exist, and allow economists to determine the possible economic viability of these resources in the region. Thus, mineral deposit models play the central role in transforming geoscience information to a form useful to policy makers.

Although there are many fine compendiums of mineral deposit models (Anom., 1995; Ekstrand and others, 1995; Roberts and Sheahan, 1988; Rongfu, 1995; Sheahan and Cherry, 1993), the focus here is on deposit models applied to quantitative resource assessment. Thus, the discussion here is limited to mineral deposit models specifically designed for quantitative assessments, such as those in Cox and Singer (1986), Bliss (1992a), and Rogers and others (1995). The target population of these assessments is the undiscovered mineral deposit that is defined as a mineral occurrence of sufficient size and grade that it might, under favorable circumstances, be economic.

Because every mineral deposit is different from every other in some way, models have to represent more than single deposits. Deposits sharing a relatively wide variety and large number of attributes come to be characterized as a "type," and a model representing that type can be built. Probably the most important part of building mineral deposit models is the planning stage in which consideration of the purpose and possible uses of the models should determine the character of the models. Ideally, deposit models would provide the necessary and sufficient information to discriminate: (1) possible mineralized environments from barren environments, (2) types of known deposits from each other, and (3) mineral deposits from mineral occurrences. In quantitative assessments, deposit models are used to classify mineralized and barren environments and to classify types of known deposits in the delineation part of the assessment, whereas mineral deposits are distinguished from mineral occurrences in the number of deposits estimation part of the assessment. The grade and tonnage parts of deposit models, combined with the estimation the number of undiscovered deposits, provide the foundation for economic analysis.

In most published quantitative mineral assessments, two kinds of models have been relied upon—descriptive, and grade and tonnage. Examples of a third kind of model that represents the number of deposits per unit area have appeared sparingly—each of these kinds of models is discussed briefly below.

Descriptive models, such as those in Cox and Singer (1986), have two parts. The first describes the geologic environments in which the deposits are found; the second gives identifying characteristics of deposits. Thus, the first part plays a primary role in the delineation process in that it describes the general setting of the deposit type. The second part helps classify known deposits and occurrences into types which aids the delineation process. In some cases, geologic environments not indicated on geologic maps are identified by the types of known deposits and occurrences. The organization of the models constitutes a classification of deposits. The arrangement used emphasizes easy access to the models by focusing on host-rock lithology and tectonic setting, the features most easily obtained from a geologic map.

Grade and tonnage models (Cox and Singer, 1986; Bliss, 1992a) combined with estimates of number of deposits are the fundamental means of translating geologists' resource assessments into a language that economists and others can use. For each deposit type, these models help define a deposit, as opposed to a mineral occurrence or a weak manifestation of an ore-forming process. Data utilized to construct these models include average grades of each metal or mineral commodity of possible economic interest and the associated tonnage based on the total production, reserves, and resources at the lowest possible cutoff grade. These data represent an estimate of the endowment of each of many known deposits so that the final models can accurately represent the endowment of all undiscovered deposits.

An important consideration at the data gathering stage is the question of what the sampling unit should be (Singer, 1993). Grade and tonnage data are available to varying degrees for districts, deposits, mines, and shafts. In many cases old production data are available for some deposits and recent resource estimates are available for other deposits. Probably the most common error in constructing grade and tonnage models is mixing old production data from some deposits with resource data from other deposits. It is critical that all data used in the model represent the same sampling unit because mixing data from deposits and districts or old production and recent resource estimates usually produces bimodal or at least non-lognormal distributions and may introduce correlations among the variables that are artifacts of the mixed sampling units. Models constructed using data from mixed sampling units are of questionable value because the frequencies of tonnage and grade observed are directly related to the proportion of deposits from each sampling unit and are unlikely to be representative of the proportion in the undiscovered deposits being estimated in an assessment.

It has been suggested that the grade and tonnage models should be extended to include not only deposits but occurrences. If the problem of possible biases due to incomplete exploration of these occurrences is neglected, then it is possible to construct such models; the tonnage model would of course have a much lower median. Because quantitative assessments require that the estimated number of undiscovered deposits be consistent with the grade and tonnage model, the process of estimating the number of deposits might be more difficult because of the much larger number of "deposits" to be estimated. An economic analysis of the results of this assessment would show that the occurrences and probably some of the estimated undiscovered deposits would be uneconomic. Thus, the effect of including occurrences in the grade and tonnage model would be to make more work in the assessment and not affect the final answer in any way.

A key function of many quantitative mineral resource assessments is estimation of the number of undiscovered deposits. Numerous techniques can be used directly or as guidelines to make these estimates. Most robust of these methods is a form of mineral deposit model wherein the numbers of deposits per unit area from well-explored regions are counted and the resulting frequency distribution is either used directly for an estimate or indirectly as a guideline in some other method. Number of deposits per unit area ratios can be used in histograms to show how commonly different deposit densities are. It is not necessary that the base areas are explored completely, but it is necessary that the number of deposits found and the proportion of the area explored be estimated. Examples of mineral deposit density models are presented by Bliss (1992b), Bliss and Menzie (1993), Singer (1994), and Singer and others (in press). The deposit densities for low-sulfide quartz gold veins are discussed by Bliss and Menzie (1993). These mesothermal deposits are defined in the descriptive model and the deposit density model is also consistent with the grade and tonnage model. It is important to note that the same proximity rule used to construct the grade and tonnage model (workings within 1.6 km of each other are treated as part of the same deposit) was used to define deposits for the deposit densities. Many of the specially selected areas where deposit densities have been reported provide standards to identify what should be high estimates of number of undiscovered deposits in most situations.

The application of these models to resource assessments helps to identify how the models should be augmented. To avoid the situation where every deposit is considered unique and therefore prediction is not possible, the deposits in an area should be tested to see if they are different from the general model. If the well-explored (that is, completely drilled) deposits are significantly different in size or grade, then the local deposits should be examined to see if they belong to a geologically homogeneous subset of the original grade and tonnage model. Only if all of these conditions are met should a new submodel be constructed along with a consistent descriptive model. The revised model would then be used in conjunction with the number of deposits estimates.

Quantifying mineral deposit attributes is the necessary and sufficient next step in statistically classifying known deposits by type. The same information is necessary but not sufficient to discriminate barren from mineralized environments; quantifying the attributes of barren environments is also necessary for this task. In order for the models of number of deposits per unit area and the attempts to quantify deposit attributes to be useful in quantitative assessments, they must be constructed so that they are consistent with the present descriptive and grade and tonnage models. Without taking this care, the resulting resource assessments would be internally inconsistent.

Consistency in quantitative assessments is a direct consequence of the internal consistency required in the construction of the descriptive, grade and tonnage, and deposit-density models. New models of number of deposits per unit area and other quantitative extensions to the present models also need to be consistent with the other parts of the models. That is, these models must be constructed from deposits that are located in geologic settings that match the descriptive models and that are consistent with the appropriate grade and tonnage models. These new versions of deposit models, the quantification of models in general, and the development of guidelines or direct methods of estimation of number of undiscovered deposits will all be successful to the extent that they are consistent with the other models used in assessments.

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# Estimating amounts of undiscovered mineral resources

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Information from mineral-resource assessments is used for making wise decisions concerning land use, development, and exploration, and for shaping minerals-related domestic and foreign policy. Quantitative assessments are required in order to make resource assessments and their associated uncertainties explicit and reproducible and to allow economic analysis. The goal is to make unbiased quantitative assessments in a format needed in decision-support systems so that the consequences of alternative courses of action can be examined.

Of the many kinds of quantitative mineral resource assessments (Shulman and others, 1992; Harris, 1984), there is one, called a three-part assessment (Singer, 1993; Drew and others, 1999), that was designed to respond to the broad goal above. In three-part assessments: (1) areas are delineated according to the types of deposits permitted by the geology, (2) the amount of metal and some ore characteristics are estimated by means of grade and tonnage models, and (3) the number of undiscovered deposits of each type is estimated. To these parts, economic analysis and proper combinations of the parts by simulation (Root and others, 1992) can be applied. Considerable care must be exercised in quantitative resource assessments to prevent the introduction of biased estimates of undiscovered resources. In three-part assessments, estimates are internally consistent in that delineated tracts are consistent with descriptive models, grade and tonnage models are consistent with descriptive models, grade and tonnage models are consistent with known deposits in the area, and estimates of number of deposits are consistent with grade and tonnage models. Biases can be introduced into these estimates either by a flawed grade and tonnage model or by the lack of consistency of the grade and tonnage model with the number of deposits estimates.

In order to be consistent, areas are delineated where geology permits the existence of deposits of one or more specified types. These areas, called permissive tracts, are based on geologic criteria derived from deposit models that are themselves based on studies of known deposits within and outside the study area. Permissive boundaries are defined such that the probability of deposits of the type delineated being occurring outside the boundary are negligible; that is, less than 1 in 100,000. Using this definition, it is possible to subdivide a permissive tract into two or more parts that have different kinds of information or possibly different numbers of undiscovered deposits. Other less stringent definitions of delineation boundaries have been considered, but they are difficult to define in a manner that can be consistently applied and they may exclude areas that contain rare but very large deposits.

Tracts may or may not contain known deposits. Areas are excluded from these tracts only on the basis of geology, knowledge about unsuccessful exploration, or the presence of barren overburden exceeding some predetermined thickness. Thus, the fundamental information is the geologic map and extensions of geologic units under cover as extrapolated or interpolated by geologic and geophysical considerations. Information from geochemistry and known deposits and occurrences helps identify permissive environments and, in some cases, excludes areas.

Designation of a tract as permissive does not imply any special favorability for the occurrence of a deposit, nor does it address the likelihood that a deposit will be discovered there if it exists. Favorability for a deposit type is represented by the number of undiscovered deposits that are perceived to exist in a tract.

The third part of an assessment is the estimate of some fixed, but unknown, number of deposits of each type that exist in the delineated tracts. Until the area being considered is thoroughly and extensively drilled, this fixed number of undiscovered deposits, which could be any number (including 0), will not be known with certainty.

Estimates of number of deposits explicitly represent the probability (or degree of belief) that some fixed but unknown number of undiscovered deposits exist in the delineated tracts. As such, these estimates reflect both the uncertainty of what may exist, and a measure of the favorability of the existence of the deposit type. Uncertainty is shown by the spread of the number of deposits estimates associated with the 90- to the 10- or 1-percent quantiles—a large difference in the numbers suggesting great uncertainty. Favorability can be represented by the estimated number of deposits associated with a given probability level, or by the expected number of deposits.

Estimates are by deposit type and must be consistent with the grade and tonnage model and not with the population of *mineral occurrences*. Thus, the estimated number of deposits must match the percentile values of the grade and tonnage model. For example, for any estimate, approximately half of the estimated undiscovered deposits should be larger than the median tonnage and about ten percent of the deposits should be as large as the upper ten percent of the deposits in the tonnage model. If the grade and tonnage model is based on district data, then the number of undiscovered districts should be estimated. Some of the models were constructed with spatial distance rules such as a 500m rule for combining mineralization—the same rule must be applied when the number of undiscovered deposits is estimated. Deposits in the study area that have published grades and tonnages are counted as discovered deposits—those without published estimates are counted as undiscovered in order to avoid double counting.

There are no fixed methods for making estimates of number of undiscovered deposits. On the basis of experience and logic, however, there are a number of ways that can be used directly or as guidelines to make these estimates.

**Guidelines for number of deposits estimates**

- Frequency of deposits from well-explored areas *(US, Alaska—MacKevett and others, 1978: Western US—Drew and others, 1986: Costa Rico—Singer and others, 1987: Venezuela—Cox, 1993: Australia—Scott, 2000: general—Bliss and Menzie, 1993)*

- Local deposit extrapolations *(US, Alaska—Singer and MacKevett, 1977: US, Alaska—Root and others, 1992: Japan—Kouda and Singer, 1992:)*

- Counting and assigning probabilities to anomalies *(US, Alaska—Reed and others, 1989: Puerto Rico—Cox, 1993)*

- Process constraints *(Worldwide—Drew and Menzie, 1993)*

- Relative frequencies of related deposit types *(Worldwide—Drew and Menzie, 1993)*

- Area spatial limits *(Worldwide—Singer and Mosier, 1981)*

- Total known metal *(US—unpublished)*

Each guideline represents some form of analogy. Most robust of these is a form of mineral deposit model wherein the number of deposits of each type per unit area from well-explored regions is counted and the resulting frequency distribution is either used directly for an estimate or indirectly as a guideline in some other method. Although Allais (1957) employed this method of estimating number of undiscovered deposits, many kinds of deposits were mixed together in his analysis.

In most three-part assessments, the final estimates have been made subjectively and many have employed one or more of the above methods as guidelines. Using a variety of different guidelines for estimates provides a useful crosscheck of assumptions that were relied upon.

In practice, a small group of scientists who are knowledgeable about the deposit type (and advised by the regional experts) typically make consensus estimates. Two general strategies tend to be used (Menzie and Singer, 1990): 1. Individual occurrences, prospects, and indicators are assigned probabilities and the results combined; and 2. The estimator recalls from experience many other areas that are geologically similar to the area being assessed (and are well explored) and uses the proportion of these other areas having different numbers of deposits to make the estimates for the new area. In each case, the scientists must weigh all of the geoscience and exploration information. Until more estimation guidelines and density of deposits models are available, it seems prudent to rely on mineral deposit specialists to make subjective estimates because they can bring their experiences and observations to the process.

Subjective probabilities such as used here have been variously called degrees of belief or propositional probabilities. Geologists commonly make estimates that, although not explicitly quantitative, are subjective and have uncertainty, such as making geologic cross sections. Examples from different fields (Murphy and Winkler, 1984; Stern, 1991) demonstrate that at least under some conditions subjective estimates can be unbiased and reliable. The decades of experience of subjective and objective forecasting in meteorology provide insight into how the process of making subjective assessments in mineral resources might be improved. Murphy and Winkler (1984) found that consensus schemes performed better than almost all individual forecasters and that the best forecasts were made when objective forecasts were part of the information supplied to subjective forecasters. Among their recommendations were: more effective use of many information sources; motivation to encourage forecasters to improve their performance; provision of formal procedures to assist forecasters in quantifying their uncertainty in terms of probability; and quick and extensive feedback concerning performance. Quick and extensive feedback might be difficult to apply in mineral resource assessments, except possibly through training exercises.

Sensitivity analysis shows that the greatest opportunity for reducing uncertainty in exploration and resource assessment lies with lowering the uncertainty associated with tonnage estimates (Singer and Kouda, 1999). This means that selection of the proper grade and tonnage model is probably more critical to the final assessment than small errors in the number of deposits estimates.

It is important to note that three-part assessments are a form of product, not a method, and therefore do not preclude the use of any method that is consistent with the other parts of the assessment. We should always use the best possible methods of making quantitative assessments. The fundamental strength of this form of assessment is its internal consistency. In these assessments, the estimates are internally consistent in that delineated tracts are consistent with descriptive models, grade and tonnage models are consistent with descriptive models, grade and tonnage models are consistent with known deposits in the area, and estimates of number of deposits are consistent with grade and tonnage models.

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# Mineral Resources Information and Socio-Economic Development

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The contribution of mining to sustainable development needs to be considered in terms of economic and technical viability, ecological sustainability, and social equity. Governments, mining companies, and local communities as well, must work and cooperate on these issues through the different stages of a mining project and over a considerable time span, extending from exploration to mine operation and to post-mine closure. As shown by World Bank's experience in mining sector development in recent years, such principles have to be taken into account even at the very early stages of regional mineral resources assessment.

Sustainable resource-use planning requires that areas of mineral potential are evaluated in the context of existing and alternative land-use options, integrating social, environmental, cultural, and economic factors. Civil society and governments are increasingly aware that minerals form only one component of a country's resources. An integrated approach, which calls for a strategic and participatory process of analysis, debate, capacity strengthening, planning, and action, involving all stakeholders – including local communities, is the only way to optimized mineral resources exploitation from a sustainable development point of view, and to identify and avoid potential conflicts in land-use. To develop such a process in a rational and fair manner inevitably requires accurate data depicting the available resource-base, as well as the transparent and open sharing and coordination of multi-user information.

The availability of strategic information with respect to mineral resources constitutes one of the main mandates of most national Geological Survey Organizations. The World Bank has long recognized the importance of Geological Surveys as "enablers" to provide the required data to make well-informed decisions regarding sustainable land and resource use and, within the framework of mining sector reforms, has provided loans to development projects that include the strengthening of these institutions, the collation and dissemination of regional multi-disciplinary geo-scientific data, and the development of information and management systems. The availability of modern and reliable geo-scientific data enhances the capacity not only to assess and manage mineral resources, but is also applicable to agriculture, forestry, environmental and health risk analysis, conservation, and land-use planning.

A recent and particularly illustrative case history is represented by the development in Ecuador of such an integrated geo-scientific data base by the National Directorate of Geology, with the assistance of the British Geological Survey. Other examples include Argentina, Bolivia, Burkina Faso, Mauritania, Mozambique, and Papua New Guinea.

**Global Nonfuel Mineral Resources and Sustainability**

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Sustainable development is a normative term such as liberty and equality. In 1994, the Enquete Commission on "Protection of Man and the Environment" set up by the German Bundestag (parliament), formulated four rules for implementing sustainable development that can be applied worldwide. With respect to the use of non-renewable resources, Rule 2 says in brief that "The consumption of non-renewable resources should not exceed the amount that can be substituted by functionally equivalent resources or replaced by finding other solutions."

The current annual world consumption of mineral and energy resources is about 25 x $10^9$ tonnes with a value of about 1.6 x $10^{12}$ DM. One can ask whether we can maintain this level of consumption and still fulfil the requirements of the concept of sustainable development, particularly in view of the fact that man has consumed more resources since World War II than during the whole of his long history before that.

The future availability of resources is usually estimated using the expression: reserves lifetime = known reserves divided by current annual consumption. The figure of reserves lifetime is influenced by many factors such as type of deposit, distribution of reserves according to deposit size, costs, and price level. In practice, reserves lifetime is a completely inappropriate measure of future availability. It is nothing more than a statistical "snapshot" of a dynamic system, which says much more about the need for innovation than about the true future availability. Innovations are essential to ensure that functionally equivalent substitutes are continually found for scarce resources, as suggested by the rules of the Enquete Commission.

If one really wishes to understand the future supply of mineral resources, one must consider the supply-and-demand cycle for mineral resources. However, it is essential to consider it in connection with one further resource – human creativity. The supply-and-demand cycle for mineral resources is driven primarily by the price of the resource, although it should be noted that psychological aspects such as increased environmental awareness also play a role. In fact, seen in the light of the Enquete rule mentioned above, which implies that functionally equivalent substitutes must be continuously found for exhausted resources, discovery of new reserves is only one, temporary, alternative solution. Other solutions are: increasing the efficiency of the resource by means of enhanced recovery from mineral deposits, by improved recycling, or by reduction of consumption by more efficient utilisation.

The aim of mineral resources policy in the sense of sustainable development must be to utilise, where possible, the resources at the base of the hierarchy to conserve resources at the top. This may be achieved by means of a materials-flow law maximising the utilisation of waste products and minimising the disposal of waste, by optimal regional policies permitting unimpeded access to bulk mineral resources, as well as by laws encouraging environmentally compatible mineral extraction. Consideration of tonnages alone is not a helpful exercise in this context.

If one considers the resources hierarchy and takes into account the potential for innovation expressed in successive learning curves, then there is no need to fear that in our market economy the supply-and-demand cycle will not in the long term always guarantee an adequate supply of mineral resources.

# Databases of known deposits, World Minerals Geoscience Database Project

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The goal of the World Minerals Geoscience Database Project is to provide high quality data sets that can be maintained and enhanced over the long term. These data will describe mineral deposits and bedrock geology to facilitate resource assessment, environmental modeling, land-use planning, and paleotectonic reconstruction in order to understand our land masses and mineral wealth. Ultimately, the goal is to provide a continuously updated global mineral deposit database that will be available over the Internet. This will be accomplished in two two-year cycles (1998-2000 and 2000-2002), under industry sponsorship. In cycle one, a data model was developed and supported with a database entry program. Input and requests from experts involved in compiling data sets on nickel, PGE, chromite, porphyry-related, MVT, Sedex and lode gold deposits helped develop the model and utilities which are still being fine-tuned. In cycle 2, the deposit databases will be made more accessible to the end user through a graphical query interface that will allow interactive filtering and the extraction of spreadsheet, report, and display output. Existing databases, including R. V. Kirkham's updated sediment-hosted copper data set, will be enhanced and a new database on Fe-oxide-copper-gold will be initiated.

Emphasis is on the most fundamental parameters of deposit geology, age, and tectonic setting. Attributes such as host-rock class and tectonic setting must be broken down into their elements and generalized enough that the main classifiers for each geological or tectonic attribute can be described in terms of less than twenty-five discrete values to be queried in a meaningful way. Compilers are challenged to contribute to the provision of these parameters, and suggestions from this workshop will also be seriously considered. Production and resource figures, as they are captured from source publications, are included in these data sets. The databases are well referenced, and the type of information taken from each data source can be indicated, a feature which will help maintain confidence as the data are updated by multiple compilers.

Queries on these databases based on tectonic setting and presence of certain host rock classes, in conjunction with production-reserve reports, could support steps of a resource assessment process. The generalized geology data set, which also accommodates setting and host rock information, could provide areal components needed for other steps when it is sufficiently populated. On the other hand, the accuracy of deposit locations in our databases is currently insufficient for resource modeling applications dependent on GIS integration with detailed (1:50,000 to 250,000 scale) geological GIS data sets.

Accurate deposit locations, valued highly by exploration companies, will become important to everyone as other global satellite scenes and land management data sets become more widespread and environmental aspects of development can be monitored. Therefore, the global databases should be synchronized with those of more local authoritative geoscience agencies that are currently using GPS technology to improve their location data. Internet technology might be used to provide nested ‘views,’ with the global database(s) providing global context and local databases providing additional land tenure, development, and detailed descriptive information. Human resources and interagency cooperation will be needed to accomplish this goal.

## BIOGRAPHIES

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Dr. Briskey graduated Oregon State University in 1975, with a Ph.D. in geology and economic geology and a doctoral thesis on the "Geology, petrology, and geochemistry of the Jersey, East Jersey, Huestis, and Iona porphyry copper-molybdenum deposits, Highland Valley, British Columbia." He joined the USGS in Menlo Park, California, in 1975, where he conducted geologic and mineral-deposit modelling research, and served as commodity geologist for zinc and lead. His research there also included geologic research and mineral-resource assessments of 2-degree quadrangles and of Indian lands in the western United States, together with studies of Mississippi Valley-type zinc deposits in the southern Appalachians. In 1985, Dr. Briskey became Associate Chief of the Branch of Western Mineral Resources, and in 1988, was transferred to USGS headquarters in Reston, Virginia, to become Deputy Chief of the Office of Mineral Resources, and Program Coordinator for the National Mineral Resources Assessment Program. In 1994, Dr. Briskey was awarded a Brookings Institution LEGIS Congressional Fellowship and served for two years on personal and committee staff in the United States Senate. Dr. Briskey presently is conducting research and research development in three major areas: (1) A Feasibility Study for a Global Nonfuel Mineral Resource Assessment; (2) Resource and Environmental Assessments of Iron and Steel Slag Along the Shore of Lake Michigan; and (3) a new Integrated Science Project with the USGS Biologic Resources Division to investigate uses of "Mineral-Resource Assessments for Protecting Ecosystem Biodiversity and Health While Planning Nonfuel Mineral Supply in the Next Century." Dr. Briskey serves on a number of committees for the American Geological Institute, Society of Economic Geologists, and International Association for the Genesis of Ore Deposits.

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Lesley Chorlton is a graduate of McGill University (B. Sc. 1968; M. Sc., 1973) and Memorial University of Newfoundland (Ph. D., 1984). She was regional geologist, Southwest Newfoundland, for the Government of Newfoundland and Labrador during the federally and provincially funded agreement to complete geological mapping of Newfoundland, 1977-82. After working as a regional economic geologist for the Ontario Geological Survey, 1984-89, she redirected her career to geological applications of geographical information systems, obtaining a diploma at Sir Sanford Fleming School of Natural Resources. Developing an information system for the generalized geology of the world, and functioning as data manager for the world mineral deposit databases of the World Minerals Geoscience Database Project, Geological Survey of Canada, have since been her principal occupations.

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Charles (Skip) Cunningham is a research geologist with the U.S. Geological Survey (USGS) in Reston, Virginia. He is an economic geologist specializing in ore deposits in volcanic and subvolcanic environments, fluid-inclusion geothermometry and geobarometry, and light-stable isotopes, as applied to problems of ore genesis and mineral resource evaluation. He received his

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Erik was born and raised in Namibia and studied geology at the universities of Stellenbosch and Pretoria in South Africa. In 1969 he spent a year in Germany under a Von Humboldt Fellowship. After a short spell at the Tsumeb Mine in Namibia, he joined the then Geological Survey of South Africa. He worked most of his life in economic geology and metallogeny and was instrumental in the production of various publications on the mineral resources of southern Africa, metallogenic maps, and the creation of mineral resource databases. The Mineral Resources Handbooks and Metallogenic Maps of South Africa (1:1 million), and the Metallogenic Map of Africa (1:5 million) with its attendant database, are cases in point. Internationally he participated in various endeavours, notably ISMI, the CGMW and IAGOD. Currently he is President of the CGMW's Subcommission for the Metallogenic Map of the World, and First Vice-President of IAGOD; he served the Geological Society of South Africa as President in 1992/93. Erik presently is Manager of Strategic Planning for the Council of Science (formerly the Geological Survey of South Africa).

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Kathleen M. Johnson has geology degrees from Smith College (AB with honors, 1972) and Syracuse University (MS, 1974). She joined the U.S. Geological Survey in 1975, working on Alaskan projects from Menlo Park, California. Since then she has been assigned to Denver, Colorado; Spokane, Washington; and Reston, Virginia, and has worked on mineral resource and glacial studies in Alaska; on mineral resource assessments in Idaho, Nevada, Utah, Texas, and New Mexico; and on minerals projects in Papua New Guinea, Venezuela, and Tanzania. In 1989, she established the USGS Minerals Information Office in Spokane. Since 1998 she has served as Program Coordinator for the Mineral Resources Program. Kate's career has also included leadership roles in the Association for Women Geoscientists, American Geological Institute, Society of Economic Geologists, Geological Society of America, and Spokane Federal Executive Association. She presently chairs the IUGS-UNESCO Deposit Modeling Programme.

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Dr Ian Lambert is a Group Manager within the Australian Geological Survey Organisation. He leads and manages the National Projects and Advice functions, which are conducted by a group of some 45 scientists. After receiving his Ph.D. from the Australian National University, Dr Lambert spent some 18 years conducting research on mineral deposits, Earth evolution, and various other subjects. In the course of his research career, he received several international awards and other funds, which enabled him to visit mines and institutes in many parts of the world. Since 1990, Dr Lambert has worked in the Australian Government, where he has held a series of senior management positions related to resource access, land and water management, and environmental protection. In August-September 2000, he is visiting several countries to discuss scientific inputs to policies and decisions on sustainable development, funded by an Australian Senior Executive Fellowship.

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Robert Laramée is a geologist and computer scientist. He obtained his B.Sc. in geology in 1969 from Université de Montréal, and a Certificat en informatique de gestion in 1984 from Université du Québec à Hull. Robert first worked for the Geological Survey of Canada in 1967 and joined the Geomathematics Section, Mineral Resources Division, in the fall of 1971. He also taught computer science at Université du Québec à Hull in 1989. Robert's main interest is in the application of information technology to the solution of geological (especially mineral deposit) problems. His activities have ranged from programming geographic coordinate conversions to designing mineral deposit databases. Robert is currently working on the World Minerals Geoscience Database Project as mineral deposits database specialist. His main activity is the development of a database schema suitable for any type of mineral deposits on a world scale, and of accompanying software tools to enter and edit data, to safely upgrade the database schema, to interrogate the database, and to produce output in a variety of formats.

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Bruce R. Lipin was born in New York City, USA, in 1947. He attended undergraduate school at City College of New York and Graduated with a B. S. in Geology. He received his Ph. D. in Mineralogy-Petrology from the Pennsylvania State University in 1975. He has been with the U.S. Geological Survey since 1974 and has done research in lunar experimental petrology, the origin and distribution of mineral deposits – specializing in chromite and platinum, layered igneous complexes – especially the Stillwater Complex in Montana, USA. He is currently the chief of the USGS minerals database project and is a part of the global mineral-resource assessment feasibility team.

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George A. Nooten has been in the service of UNRFNRE for the past 21 years. He has acquired extensive international experience through designing, planning, negotiating agreements, and managing the execution of mineral exploration programs in several developing countries including Tanzania, Mozambique, Cote D'Ivoire, Sierra Leone, Ghana, Yemen, and Sri Lanka. His most recent discoveries are the Geita Hill and Nyamulilima gold deposits in Northwestern Tanzania. The 12-million-ounce Geita mine was opened on August 3, 2000. Prior to joining the UNRFNRE in 1979, he worked as Chief Geologist for the bauxite mines in Linden, Guyana, and as a geologist for the Iron Ore Company of Canada, INCO, and the Quebec Ministry of Natural Resources. He undertook his undergraduate studies in geology at Queens University, Kingston, Canada, and received a M.Sc (Minex) from the same University.

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Dr. Klaus J. Schulz is a research geologist with the U.S. Geological Survey (USGS) in the Eastern Mineral Resources Team, Reston, Virginia. He currently directs USGS efforts to evaluate the feasibility of conducting quantitative global assessments of undiscovered non-fuel mineral resources. He has previously directed and/or participated in several regional and detailed-scale mineral-resource assessments, including the USGS-Costa Rican National Mineral Resource Assessment and the U.S. National Mineral Resource Assessment for Undiscovered Deposits of Gold, Silver, Copper, Lead, and Zinc. He has also organized and co-directed several workshops, the most recent being the IUGS/UNESCO Deposit-Modeling Workshop on Base- and Precious-Metal Deposits in the Arabian Shield, November 12-19, 1999, in Jiddah, Saudi Arabia. Dr. Schulz's research has focused on the metallogeny of Precambrian terranes, and on volcanic-hosted and magmatic sulfide mineral deposits. He is the current USGS member of the IUGS/UNESCO Deposit Modeling Program steering committee and the IUGS Subcommission on Precambrian Startigraphy. He served as the Chief of the Branch of Eastern Mineral Resources from 1989 to 1996. Dr. Schulz holds a B.S. degree in Geology from the University of Wisconsin, a M.S. degree in Petrology from the University of Minnesota, and a Ph.D. in Igneous Petrology/Geochemistry from the University of Minnesota.

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Dr. Deborah Shields is Principal Mineral Economist for the U.S. Dept. of Agriculture, Forest Service, Research and Development Division. She directs the agency's energy and mineral economics and mineral policy research programs, providing technical and scientific input to the Forest Service Strategic Plan, the Resource Planning Act Assessment, and the National Forest planning process. In addition, she leads the agency's effort to include nonrenewable resources in sustainable forest management, working with stakeholders in other government agencies, Tribal governments, industry, academia, and non-governmental organizations to develop indicators of sustainability for energy and mineral resources. She has organized and will be Co-director of an Advanced Research Workshop (ARW) entitled Sustainable Mineral Resource Management in Karst Areas. The ARW is sponsored by the NATO Scientific Affairs Division, and also by UNESCO, UNEP, the USDA Forest Service, and the Geological Survey of Slovenia. Deborah also provides technical support on sustainability issues to the U.S. delegation to the meetings of the Mining Ministers of the Americas. Finally, she is Program Manager for Human Dimensions Research for the Front Range Ecosystem Management Project. Prior to working for the Forest Service, Dr. Shields worked for the U. S. Dept. of Interior, Bureau of Mines, specializing in international mineral supply, and trade analysis and forecasting. She has published in the areas of sustainability policy and theory, utility theory and welfare economics, decision theory and decision support systems, and network modelling. She holds a B.S in Wildlife Management from Colorado State University, a Master of Science in Mineral Economics from the Colorado School of Mines, and a Ph.D. in Rangeland Ecosystem Science from Colorado State University.

**W. David Sinclair, Geological Survey of Canada**

Dave Sinclair is a graduate of the University of Toronto (B.Sc., 1966) and the University of Wisconsin (M.Sc., 1970; Ph.D., 1973). From 1973 to 1977, he was employed by the Department of Indian Affairs and Northern Development in Whitehorse, Yukon Territory as a district geologist and was acting Resident Geologist in 1976-77. In 1977, he joined the Geological Survey of Canada in Ottawa, where he has specialized in the geology of granite-related mineral deposits. He currently manages the World Minerals Geoscience Database Project.

**Donald Singer, U.S. Geological Survey**

Don is primarily interested in the application of quantitative methods to mineral resource assessments and exploration. He has written over 200 papers on resource assessments, deposit models, quantitative methods, and exploration strategies. Recent work has been on developing and testing methods such as neural networks to integrate geoscience information for resource assessments and exploration. The Society of Economic Geologists awarded him its Silver Medal in 1999. He has been a Geologist with the U. S. Geological Survey in Menlo Park, California, since 1973. Prior to this, he was a System Analyst with Kennecott Copper. Don holds a PhD in mineralogy and petrology from The Pennsylvania State University.

**Milica Veselinovic-Williams, Council for Geoscience**

Mrs. Milica Veselinovic-Williams studied at Belgrade University, Yugoslavia, and obtained her BSc. (Hons.) in Geology in 1985. Subsequently, she worked as an exploration geologist for the Geoinstitut, Belgrade. In 1992, she obtained her MSc. in Exploration Geology from Rhodes University, South Africa. She joined the Council for Geoscience (formerly the Geological Survey of South Africa) in 1994 and became the main author of The 1:5,000,000 International Metallogenic Map of Africa and its database. Under her supervision, the first edition of the Subequatorial African sheets (5 and 6) were published in digital GIS format on a CD-ROM in June 1999. Milica is also extensively involved in the design and development of a number of GIS database models for the production of metallogenic maps. Address: Council for

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**Gotthard Walser, World Bank**

Dr. Walser is a Senior Mining Specialist at the Mining Department of the World Bank, Washington D.C. Through advising services or technical assistance loans, the focus of his activity is to assist Governments to develop their mining sector and promote investments leading to sustainable development through policy, legal, and institutional reforms, as well as capacity building, environmental protection, and improved community participation. He has a particular interest in the reform of public mining institutions and strengthening of governance; the development of geo-scientific, environmental and mining information systems; and in environmental and social issues related to mining. He currently leads or participates in projects in Argentina, Algeria, Burkina Faso, Ecuador, Madagascar, Mauritania, and Mozambique.
Prior to joining the World Bank in 1994, he worked with the Swedish Geological Survey, and later with its International Division, for more than 15 years, gaining broad professional and management experience. Responsibilities during this period included the planning and management of regional mapping and mineral resource assessment programs, as well as ore exploration, mine evaluation, and development projects; this work occurred through assignments both in Sweden and overseas, including many African and, particularly since 1982, Latin American countries. Dr. Walser holds a B.Sc., M.Sc. and Ph.D. in Earth Sciences from the University of Geneva in Switzerland.

**F.-W. Wellmer, Bundesanstalt für Geowissenschaften und Rohstoffe**

Prof. Dr.-Ing. Dr. h.c. Wellmer is President of the Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources). He studied mining and geology at the Technical Universities Berlin and Clausthal. He worked for the German mining company Metallgesellschaft AG and its Canadian and Australian subsidiaries in Europe, North and South America, Australia, Oceania, and the Far East. Before joining the Federal Institue of Geosciences and Natural Resources, the Federal German Geological Survey BGR in Hannover, he was Director of Exploration at the Metallgesellschaft of Australia Pty. Ltd. in Melbourne. Wellmer became President of the BGR and the Lower Saxony Geological Survey in 1996. He also teaches raw materials policy and economic geology as a professor at the Technical University, Berlin. He was awarded a honorary doctorate of the Technical University Mining Academy, Freiberg, in 1999.

**John Wood, Geological Survey of Canada**

John Wood is Director of the Mineral Resources Division of the Geological Survey of Canada, and is charged with managing the Mineral Deposits Research, Environmental and Exploration Geochemistry, Airborne and Borehole Geophysics, and Assessment and Spatial Analysis programs of the Survey. Prior to joining the GSC in 1997, he worked with the Government of Ontario, where he held various positions ranging from field geologist to Director of the Ontario Geological Survey. He spent five years as Director of Mineral Development, where sustainable development practices were espoused with industry undertaking exploration and development activities in the Province. His early geological training on the hills and mountains of Scotland has made him a firm believer in the concept that the truth lies in the rocks.