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Mineral deposit models: theory and practice

(A modified version of a speech given at the First McKelvey Forum on Mineral Resources, February 6, 1985)

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INTRODUCTION

The Organic Act of 1879 gave the United States Geological Survey the responsibility for "classification of the public lands and examination of the...mineral resources and products of the national domain." Classification and examination has underlain much of the work of the Survey from the beginning. Since the start of the Wilderness Program in 1964, formal mineral assessment has grown in importance; it now forms a large part of the Survey's program in terms of both dollars and human effort. Mineral deposit models are an essential tool used in mineral assessment.

This paper is a modified version of a talk presented on February 6, 1985, at the First Annual McKelvey Forum on Energy and Mineral Resources (Krafft, 1985). We first present some thoughts about theoretical aspects of models and then show how the Geological Survey has used them over the years. The last part discusses our present and future activities in creation and use of mineral deposit models.

Each of us has something specific in mind when we hear the word "model." In this paper we make a geologically oriented definition of the word so that we all can agree as to what we're talking about. Interestingly enough, the dictionary is not too useful on this problem, an indication of how fast our language is changing in the technological fields. An important part of most definitions is the idea that the item itself is not available for direct examination, study, or use and the model is used in its place. Also important is the idea that a model can represent many different tangible items and may not itself be tangible. For our purposes, we define a mineral deposit model as:

SYSTEMATICALLY ARRANGED INFORMATION THAT DESCRIBES THE ESSENTIAL ATTRIBUTES OF A CLASS OF MINERAL DEPOSITS.

The key words here are systematic, information, and essential.

There is an important distinction between any model and the real thing. The model is nothing more than systematically arranged information. It is we geologists who collect the information and arrange it in a way that we call systematic. The deposits themselves just sit in the ground and are relatively insensitive to our opinions about them or their characteristics.

USES OF MODELS

Knowing the intended use of a model helps considerably in its construction. Different parts of models are emphasized for different uses or purposes. Five common uses of mineral deposit models are: resource assessment, estimation of commodity endowment, mineral exploration, education, and research.

An important use of models in government is resource assessment for the guidance of land-use planning. As competition for land use grows, government at all levels becomes more involved in land-use planning. Mineral deposit models aid in planning the activities that constitute the resource assessment. They also form the interface between geologic information and land planning expertise; they facilitate the careful delineation of what is sure, what is surmised, and what is suspected. A major challenge is making the conclusions clear enough to be useful to land use planners, while keeping the models sophisticated enough to accurately reflect the geologist's detailed knowledge.

Estimation of commodity supplies and endowments is becoming increasingly popular among governments all over the planet. Though there has been concern for and study of the supply of strategic and critical minerals for many years, the major impetus for the present interest in estimating endowment was the oil embargo of

1973, when many governments realized that they had little reliable information about energy supplies. The resulting furor led to a revolution in methods of petroleum supply forecasting; a quieter, smaller-scale revolution for the metals is now underway.

Models have been used in mineral exploration for thousands of years. The new game here is to explicitly call them models. It is only in the last 20 years that reference to the concept of modelling has become popular in the exploration industry.

Models are an important format for education and are used to train young geologists, as well as those more experienced. Models provide a concise and efficient way to disseminate information to those less experienced in the study of ore deposits.

Finally, working with models is an extremely valuable research guide. In preparing models, we often discover attributes and relations about which we have very little information. Thus, use of models can indicate fruitful avenues for new research.

TYPES OF MODELS

Models themselves may be classified according to their essential attributes. Familiar types of deposit models include: descriptive models, grade-tonnage models, genetic models, probability-of-occurrence models, and quantitative process models. These should not be thought of as truly discrete divisions that are not interrelated. These "types" are really aspects of a greater entity, the ideal model that we always work toward. Consider first the descriptive model, also known as the occurrence model. An organized collection of such models constitutes a classification of mineral deposits, something that has been of concern to economic geologists since the beginnings of geology. Occurrence models are the framework and basis upon which all the other types of models are built. They allow us to recognize geologic features that we observe in the field as interrelated groups and to name those groups. As our knowledge increases, occurrence models become more complex and also more specific. In the 1950s, we began to recognize the common characteristics of porphyry copper deposits: age, alteration patterns, local structural settings, and the like. Today, we are able to subdivide porphyry deposits into a number of useful subtypes on the basis of more subtle characteristics like trace metal content, tectonic setting, and petrologic affinity.

Grade-tonnage models are a means of quantifying occurrence models. They are a way of describing a particular deposit type in terms that engineers and economists can transform into economic information. Typically, cumulative frequency distributions for grade and tonnage are compiled from many examples within each deposit type. These distributions may then be used to predict the probable grades and tonnages of undiscovered deposits. A good example of grade-tonnage models is the series of 38 models prepared for the cooperative resource assessment of Colombia recently completed by the Geological Survey and the Colombian government (Singer and Mosier, 1983a,b).

Occurrence models pass imperceptibly into genetic models, which allow prediction as well as recognition. The predictive capacity of genetic models is a result of recognition of the underlying geologic processes responsible for the characteristics described in the occurrence model. The information and understanding that elucidates process often comes from fields not directly related to economic geology, such as stratigraphy, paleontology, and volcanology. For example, the realization that sedimentary manganese deposits are the result of uncommon, but nevertheless normal, understandable sedimentation processes allows us to use stratigraphic and sedimentological methods to predict terrains where such deposits may be found, even when there is no physical evidence of them (Cannon and Force, 1985).

Probability-of-occurrence models are quantifications of the predictions made with genetic models. Numerical estimates of the number and distribution of undiscovered mineral deposits are made, along with a determination of the associated uncertainty. The technology of reporting uncertainty is well developed and used routinely in fields like psychology, demographics, and meteorology. The challenge for earth scientists lies in creating the methods for assigning the probabilities. Geologic time moves too slowly to use traditional methods of hypothesis testing. Likewise, we lack "completely explored" regions that might be used as tests of our predictive capabilities. So our job is to define some non-traditional ways of measuring reliability. A good example of probability-of-occurrence models can be seen in the reports of several projects of the Alaskan Mineral Resource Assessment Program (AMRAP) and the Conterminous United States Mineral Assessment Program (CUSMAP), in which probability distributions are reported for a number of expected deposit types within specific favorable tracts (Singer and Mackevett, 1977; Eberlein and Menzie, 1978; Singer and others, 1983).

A final subtype of model is the quantitative process model, in which mass and energy transfers during geologic processes are described quantitatively. Perhaps the best-known example of these is the calculation of the amounts and sequences of minerals precipitated from evaporating sea water that have been so useful in understanding evaporite deposits (Braitsch, 1962).

MODE OF IMPLEMENTATION

Exploration geologists approach models differently than do geologists doing mineral resource assessment. Figure 1 shows a typical pattern of information flow in an exploration project. The model in question is assigned to or chosen by the explorationist. Much of the geologic information on a prospective area can be ignored from the beginning, because it is not pertinent to the model at hand. The limestone/dolomite ratio of a carbonate unit, for example, is probably not too

EXPLORATION

Starts with commodity

Mineral occurrence model

Selection of targets

Figure 1

important in exploring for porphyry deposits. As exploration proceeds, the geographic areas under consideration become smaller and the information base may contract or expand only slightly. In exploration, it all boils down to a single question...is there a target and, if so, where?

In resource assessment, the geologist unfortunately must proceed from the general to the more general, as all models must be evaluated simultaneously. Geographic areas almost never pass entirely from consideration and the information base has an alarming tendency to increase exponentially. The entry point into a compendium of models is an observed characteristic (figure 2). For example, if we observe a quartz monzonite porphyry intrusion, this brings porphyry copper deposits immediately to mind, but it also has implications for a number of other deposit types. The simplest way to process this information is a simple, but time-honored, concept known as the index. One of our future projects is to automate the indexing of characteristics via microcomputer-based data management systems. This will allow more complex questions to be asked, such as "What are the implications of quartz monzonite porphyry intruded into carbonate host rocks that overlie thick continental crust?" By making this kind of information available through simple-to-use, well known software systems, we hope to make it easily accessible to a wide spectrum of users.

ERROR TYPES

Another important difference between exploration and resource assessment can be seen in the consequences of various prediction errors. Two types of errors may occur when we make decisions about favorability (figure 3). To identify a plot of ground as barren when it actually contains a deposit may be called type A error, while to identify a tract as having a deposit when it actually is barren may be called type B error.

RESOURCE ASSESSMENT

Starts with field observations

Identification of models

Estimate probability of deposits

Figure 2

TYPES OF ERROR

TRUTH ▼ / PREDICTION ◀	deposit	no deposit
deposit	CORRECT	TYPE A ERROR (pessimistic)
no deposit	TYPE B ERROR (optimistic)	CORRECT

Figure 3

Because neither tracts nor deposits are characterized by agreed-upon spatial quanta, it is necessary to expand our concept of type A and B errors a bit to look at map patterns. Figure 4 shows all the topologically possible spatial relations between truth and prediction, as well as the resulting error types for various tracts. Situations like the one portrayed in figure 4a are the most damaging to the ego of economic geologists. Let's assume a competence level high enough that this scenario occurs so seldom that it is unworthy of analysis. Likewise, the situation shown in figure 4e requires little further discussion, because it is also highly unlikely. Figures 4b, 4c, and 4d represent situations common in the real world.

Models can be fine-tuned to be more or less selective. A highly discriminating model might decrease the probability of incorrect calls, but will result in large type A errors like those in figure 4b. A more liberal model will increase the probability of scenarios like that shown in figure 4c, which maximizes correct calls at the expense of large type B errors. If the cost of errors and the payoff for correct predictions can be calculated, it is possible to design models to maximize return. As an example, let's assume that finding the desired deposit type has a payoff of $10 million and exploring a barren system costs $500,000. Under these conditions, a success rate of less than 1 in 20 is probably not acceptable and the selectivity of the exploration model may need to be adjusted.

In resource analysis, the costs and benefits are not so easily calculated. The computational problem is not difficult: values can be assigned to anything. Land-use planners often face the necessity of assigning value to such experiences as a walk among aspen trees. It can be done. The problem is one of lack of agreement on the values. Asking 100 people how long a walk in the woods is equivalent to fifteen pounds of copper will result in many different answers. In a similar way, there are no generally accepted procedures for assigning value to deposits whose grade and tonnage do not permit present extraction. For all these reasons, U.S.G.S. geologists have avoided addressing the issue of value. As a consequence, we have

Figure 4. Five hypothetical views of the same tract. Solid lines enclose the areas that do contain mineral deposits. Dashed lines represent the area predicted in an assessment to contain deposits. Resulting error types are shown by patterns. Solid and dashed lines coincide in 4e and there is no error.

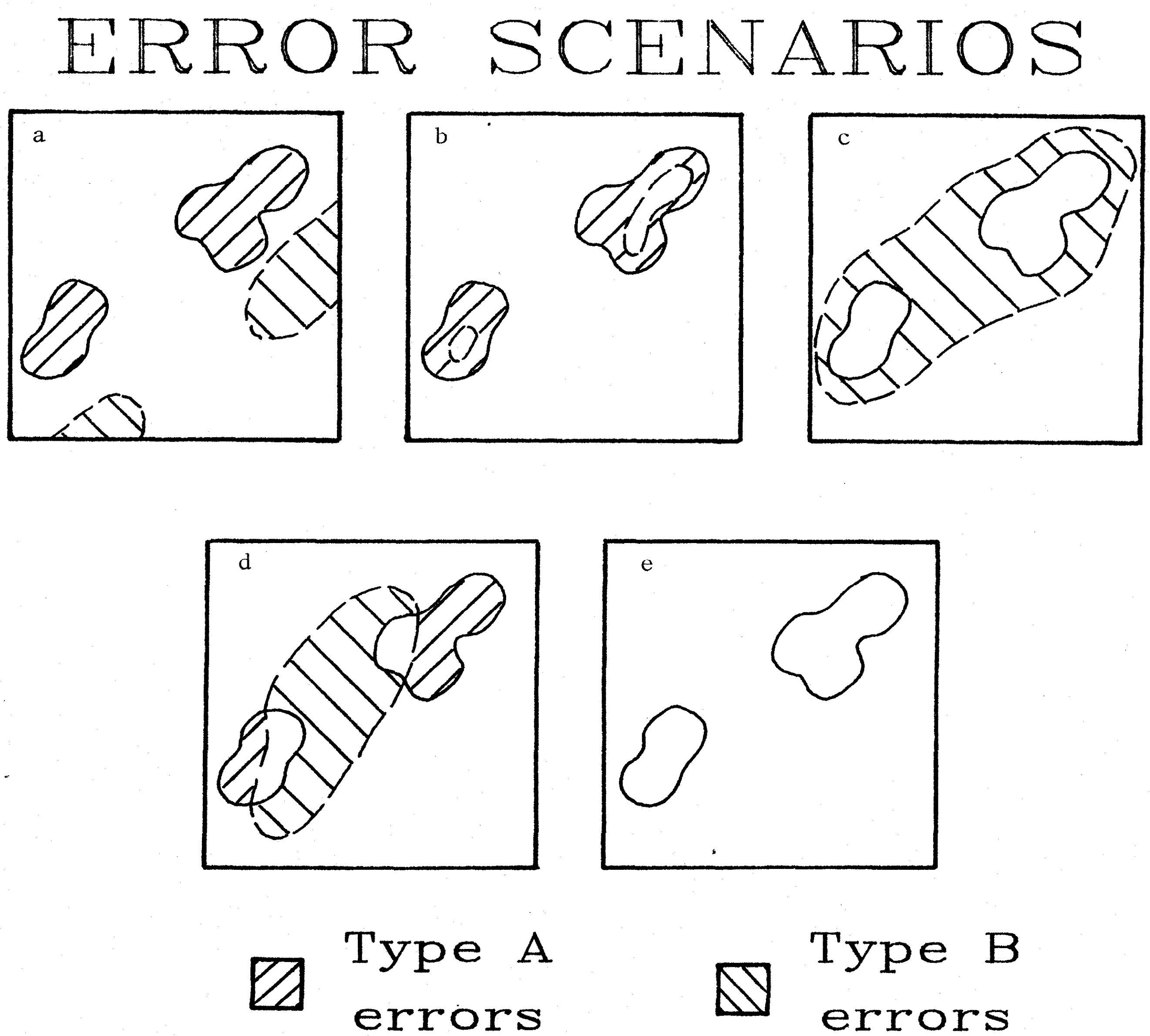

Figure 4

done little to analyze the accuracy of our models and the types of errors that we make: such analysis is an intriguing area for research.

U.S. GEOLOGICAL SURVEY MODELING ACTIVITIES

The U.S. Geological Survey has made extensive use of models (figure 5). Since the beginnings of the Geological Survey, we have produced descriptive and interpretive reports on ore deposits. In addition, numerous field conferences and workshops on the characteristics of mineral occurrences have been held.

The Forest Service Wilderness Lands program, the first phase of which was completed in 1984, was the Survey's first significant regional assessment program. Its 20 year duration witnessed the increasing visibility of models. In early reports, the use of models was largely implicit; their explicit use became quite common in the last 5 years. In addition, a new series of assessment reports on individual national forests will make extensive use of models. The prototype study for this program was published as U.S. Geological Survey Bulletin 1638 (Taylor and others, 1984).

A variety of other programs also make explicit use of models. The BLM Wilderness Lands program is just now proceeding at full speed. The Alaska Mineral Resource Assessment Program (AMRAP), begun in 1974, has made extensive formal use of models. The first grade-tonnage and probability-of-occurrence models were developed for use in the mineral resource assessment of the Nabesna quadrangle (Richter and others, 1975).

CUSMAP also makes extensive use of many of the model types we have discussed. Pratt (1981) used descriptive models in his assessment of the Rolla, Missouri, quadrangle. Singer and others (1983) used descriptive and grade-tonnage models in their appraisal of the Medford $1^{\circ} \times 2^{\circ}$ quadrangle, Oregon-California.

PROSPECTOR, a joint USGS-Stanford Research Institute effort, brought the world of artificial intelligence and expert systems into contact with economic

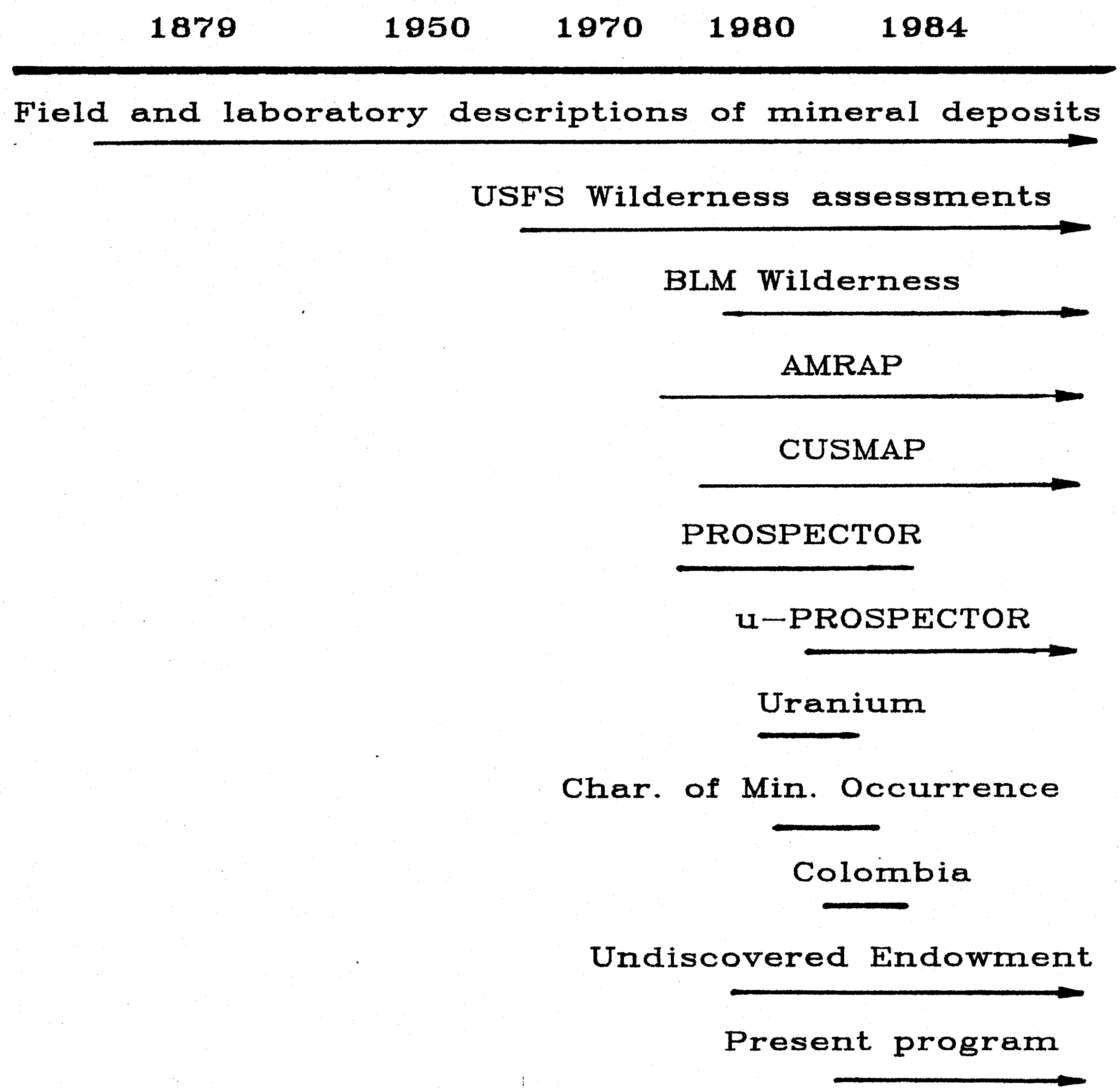
1879
1950
1970
1980
1984
Field and laboratory descriptions of mineral deposits
USFS Wilderness assessments
BLM Wilderness
AMRAP
CUSMAP
PROSPECTOR
u-PROSPECTOR
Uranium
Char. of Min. Occurrence
Colombia
Undiscovered Endowment
Present program

Figure 5

geology (Duda, 1980). PROSPECTOR is an interactive computer program that computes a numerical likelihood-of-occurrence parameter for a specific deposit type using as input the answers to a series of questions about a prospective tract. A map-based variation was also produced that, in a retrospective test, was able to predict from surface data the location of underground mineralization in a porphyry deposit in Washington state. A start has been made in linking the models together in a way such that the software can provide a list of the most likely models from the answers to a series of general questions. A simplified, microcomputer-based version of expert system, PROSPECTOR-like models is under development (McCammon and others, 1984).

Between 1977 and 1981, a series of genetic, grade-tonnage, and probability-of-occurrence models of several types of uranium deposits were developed by a team headed by Warren Finch. These models were used to estimate the undiscovered uranium endowment of the San Juan Basin in northwest New Mexico (McCammon and others, in press).

A handbook entitled Characteristics of Mineral Deposit Occurrences was published in 1982 (Erickson, 1982). Fifty models were presented, authored by various Survey experts, in an intentionally unstructured format designed to encourage creativity.

1984 was the final year for an ambitious collaboration between the Geological Survey and INGEOMINAS, the Geological Survey of Colombia. More than 50 occurrence and grade-tonnage models were compiled by Cox and Singer and published in English and Spanish (Cox, 1983a,b; Singer and Mosier, 1983a,b).

Finally, also in 1984, a consortium led by L. J. Drew published an endowment estimate for an aggregate of Pacific Coast Forest Service Wilderness Areas (Drew and others, 1984). This study used subjective probability of occurrence models and Monte Carlo simulation, coupled with Singer's grade-tonnage models, to produce esitmates of undiscovered endowment for 11 metals.

In addition to the ongoing programs that we have already discussed, U.S.G.S. geologists are making efforts to quantify attribute strength in a consistent manner. Comprehensive descriptive and genetic models for several deposit types are nearly complete and we are publishing an expanded compendium of short descriptive and grade-tonnage models that has world-wide applicability.

CONCLUSION

The list of activities in the U.S. Geological Survey that use and create mineral deposit models includes projects that focus on narrow topics, such as a single commodity, and projects that are quite broad, such as the mineral resource assessment of an entire country. As these projects continue, new information will be added to all of our deposit models and the models will become more precise descriptions of the concentrations of economic minerals we look for in the earth's crust.

The types of models we've described in this paper serve a variety of uses in the geological sciences. We have much to learn about compiling and using models in our own research and in the work we do for the use of others. However, we need to exercise care to avoid trapping ourselves in existing concepts, just because they are written down. If we confine our observations to criteria listed in known deposit models, we will fail to recognize the potential for new, as yet undescribed, deposit types. Like most other tools of the trade, mineral deposit models will serve us best when used in conjunction with all our other tools.

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