Numerical Mineral Deposit Models

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INTRODUCTION

The numerical mineral deposit models described in this paper are a part of a continuing effort to develop more quantitative approaches to assessing undiscovered mineral resources in graphically defined areas. These models have their origin in the descriptive mineral deposit models of Cox and Singer (1986). As defined by Cox and Singer, descriptive mineral deposit models represent a systematic arrangement of information summarizing the essential attributes (properties) of a class of mineral deposits. Such information is available usually in carrying out regional mineral resource assessments (Shawe, 1981). Descriptive mineral deposit models provide the geologist with a link between deposit types and geologic environments. Establishing links within a given area is the first step of the three-step assessment process described by Singer and Ovenshine (1979). The definition of this step is the delineation of areas according to the types of deposits that the geology will permit.

This decision as to which types of deposits are permitted by the geology of an area is subjective. The decision is dependent almost entirely on the experience of the geologist performing the assessment. The more experienced the geologist, the more likely the models that are selected will be the right ones. Consequently, a team approach involving geologists having knowledge about different deposit models will ensure that a wide range of possibilities will be considered. The best approach is to give the team access to geologists with expert knowledge about the deposit models being considered. The idea of giving the geologist access to experts gave rise to Prospector, an expert system developed during the mid-1970's to aid the geologist in the search for hidden deposits (Duda, 1980). Expert systems are computer programs that achieve competence in performing specialized tasks by reasoning about the task and the task domain (Feigenbaum and others, 1988). During the years of its development, which lasted until 1983, Prospector was regarded as a serious attempt to model the decision-making process involved in the application of deposit models in mineral exploration.

Since 1983, much has changed. Prospector II, the successor to Prospector, has been developed at the U.S. Geological Survey (McCammon, 1989). Two major developments have included (1) the format used to represent deposit models, and (2) the algorithm used to classify mineral occurrences, prospects, and deposits. These developments were necessary in order to (1) acquire a more comprehensive, economical, and adaptable deposit model format, and (2) accommodate changes in the use of descriptive mineral deposit models in regional mineral resource assessments (Singer and Cox, 1988). Numerical mineral deposit models have emerged as a result of these developments.

NUMERICAL MINERAL DEPOSIT MODELS

Numerical models differ from descriptive models in that numerical scores are associated with each model. A maximum score is obtained when the geologist concludes that all of the attributes of a particular model are present. However, maximum scores for different models differ. The reason is that models are made up of different attributes. In particular, two scores—one that is positive, and one that is negative—are associated with each of the attributes. A positive score reflects the degree to which a model is suggested by the presence of a particular attribute. A negative score reflects the degree to which a model is negated when a particular attribute is absent. If, on the other hand, the absence of an attribute is suggestive of a model, a positive score is associated with its absence, and a negative score is associated with its presence. Consequently, the states of presence and absence correspond, respectively, to the conditions of sufficiency and necessity in Prospector (Duda, 1980).

The attributes of numerical models are grouped into headings similar to those of descriptive models. The current headings in the numerical models are the "AgeRange," "RockTypes," "TextureStructure," "Alteration," "Mineralogy," "GeochemicalSignature," "GeophysicalSignature," and "AssociatedDeposits." In an attempt to represent the linkages within these attributes, a taxonomy has been created that facilitates these linkages. For example, under RockTypes, "Granite" is defined as a "kind-of" Felsic-plutonic RockType, which is a "kind-of" Plutonic RockType, which is a "kind-of" Igneous RockType. Thus, numerical models are characterized by generalized attributes as well as by specific attributes. This "kind-of" characterization aids greatly in limiting the number of models considered at any one time. The taxonomy that defines the attributes of the numerical models described in this paper is given in appendix C.

Virtually all of the terms listed in the taxonomy in appendix C appear as attributes in one or more of the descriptive models in Cox and Singer (1986). In creating the numerical models, the decision was made to preserve to the maximum extent possible the terminology used by the authors who contributed the descriptive models. As a result, the taxonomy does not contain terms not found in the descriptive models. Thus, the taxonomy is not a glossary of geology, but rather a glossary of terms used in the descriptive models.

Not all of the headings contained in the descriptive models are included in the numerical models. The reason is that it is not yet possible to define a taxonomy and to assign positive and negative scores for attributes that relate to headings such as "TectonicSetting," "DepositionalEnvironment," and "OreControls". Despite these shortcomings, the numerical models described in this paper offer a further means of quantifying the decision as to which mineral deposit models are permitted by the information collected in regional mineral resource assessments.

WEIGHTING OF THE ATTRIBUTES

The task of assigning positive and negative scores to attributes in the numerical models were aided greatly by the indices prepared by Barton (1986a, b) and Cox (written commm., 1987). The indices contain information on the frequency of occurrence of geochemical anomalies, minerals, and types of alteration according to the descriptive models contained in Cox and Singer (1986). Associated with each attribute was an index number ranging from +5 down through 0 to –5 in a system similar to Prospector (Duda and others, 1977). The numbers represent the commonness or rarity of each attribute. It was the intent to have the numbers 1, 2, 3, 4, and 5 correspond, respectively, to the 0–10, 10–30, 30–70, 70–90, and 90–100 percent frequency relationship between the attribute and the deposits represented by the models. In almost all instances, the numbers assigned were "best" guesses based on experience. In the future, the compilation of such data would make the assignments less subjective. For the numerical models, the attributes were each assigned a positive and negative number for each model according to the levels given in table 1. Negative levels correspond to the frequency of occurrence and express how the absence of an attribute with respect to a particular model is to be weighted. Positive levels express how the presence of an attribute is suggestive of a particular model. For instance, a Leucogranite is highly suggestive (+4) of a Sn-greisen deposit model. The known absence of Felsic-plutonic rocks in an area, however, virtually precludes (–5) the existence of Sn greisen deposits. Generally, the numbers were assigned so that they reflected as near as possible the context in which the attributes were defined by the compilers of each of the models. In the final analysis, however, the assignment is a trial-and-error process.

Table 1. Quantization levels for presence/absence of particular mineral deposit

State	Level	Verbal description
Degree of sufficiency		
Presence	5	Very highly suggestive
	4	Highly suggestive
	3	Moderately suggestive
	2	Mildly suggestive
	1	Weakly suggestive
Degree of necessity		
Absence	−1	Infrequently present
	−2	Occasionally present
	−3	Commonly present
	−4	Most always present
	−5	Virtually always present

In many cases, it was not possible even by trial and error to assign positive and negative numbers to the attributes. A rationale for assigning numbers was simply lacking. In these cases, default numbers of +2 and –2, respectively, were used.

SCORING OF THE ATTRIBUTES

The score that was assigned to an attribute in a numerical model was dependent upon the heading to which it belonged. In reviewing the descriptive models, it was recognized that the number of attributes within a heading varied from one model to the next. Different headings contained a different number of attributes. As a result, it was necessary to devise a weighting scheme that would take this into account. The intent was to balance the scores associated with each heading with the scores assigned to each attribute within each heading. In order to accomplish this, the levels in table 1 were associated with the scores given in table 2. Thus, the score associated with the highest positive (and negative) level for each heading reflects both its relative importance in defining a particular model and the number of attributes it contains. For example, the maximum score for a particular rock type cannot exceed

Table 2. Quantization levels and associated scores for mineral deposit models

[Abbreviations: Age, AgeRange; Rk, RockTypes; Alt, Alteration; Min, Mineralogy; Gx, GeochemicalSignature; Gp, GeophysicalSignature; Dep, AssociatedDeposits. Default levels: 2, presence; –2, absence]

	Presence						Absence				
Level	5	4	3	2	1	0	–1	–2	–3	–4	–5
Age:	100	40	40	40	40	0	–100	–100	–100	–100	–100
Rk:	75	60	45	30	15	0	–5	–10	–45	–60	–75
Alt:	400	300	200	100	50	0	–2	–10	–100	–200	–400
Min:	75	60	45	30	15	0	0	–5	–10	–30	–75
Gx:	75	60	45	30	15	0	0	–5	–10	–30	–75
Gp:	250	150	50	25	10	0	–10	–50	–100	–200	–250
Dep:	400	320	200	150	75	0	–50	–100	–200	–300	–400

75. However, virtually all of the numerical models are characterized by several rock types. Thus, if all types are present, the total score for rock types will be many times 75.

UNCERTAINTY IN THE EVIDENCE

In Prospector, the geologist was asked to state the degree of certainty about the presence or absence of evidence (Duda and others, 1977). The degree of certainty was expressed on a scale from +5 through 0 to –5 for which +5 was taken as absolute certainty about the presence of the evidence and –5 was taken as absolute certainty about the absence of the evidence. A value of 0 was taken to mean indifferent or "don't know." The degree of belief expressed by the geologist was used to adjust the strength of the rules relating to the evidence.

For the numerical models, a simpler method has been devised. For a given model, an attribute is judged as being present, suspected of being present (present?), missing, or absent. Absence is treated as the attribute having been looked for but not found. Missing is treated as the default, meaning that the attribute is neither present or suspected of being present nor known to be absent. If all of the attributes within a heading are missing, a default score of 0 is assigned to the heading. Thus, if no information exists on the known deposits in an area, the heading "AssociatedDeposits" is assigned a 0 score. If only some of the attributes within a heading are missing, the attributes that are missing are assigned the score corresponding to the level of –1. Attributes suspected of being present are assigned the next less positive level than the level associated with their presence. Experience to date indicates that this treatment of uncertainty in the observations is sufficient for taking into account the quality of the information available in regional mineral resource assessments.

The "AgeRange" heading is treated differently from the other headings. A statement that was made for many of the descriptive models in Cox and Singer (1986) was that deposits of the type represented by the model are restricted mainly to one interval of geologic time but may be of any age. In this sense, "AgeRange" is not particularly restrictive for these models. It was decided to assign a single score to the "AgeRange" heading—namely, a score of +100 if any part of the interval specified by the geologist lies within the interval specified by the compiler of the model, a score of –100 if it did not, a score of +40 if the geologist was uncertain about the "AgeRange," and a score of 0 if no information is available. As defined by Singer and Cox (1988), "Age" refers to the age of the event responsible for the formation of the deposit. For many areas, this age is unknown.

"TextureStructure" is not used as a basis for numerical scoring because it describes the morphology of deposits, and morphology is generally not well recognized at the time an assessment is made. If the morphology is known, the geologist tends to focus quickly on those models whose deposits exhibit these characteristics. The attributes within "TextureStructure" serve more as a checklist for identifying the types of deposit models to be considered in any given situation.

WORKSHEETS FOR NUMERICAL MODELS

Worksheets for the numerical mineral deposit models are given in appendix D. The model numbers for the numerical models correspond to the model numbers for the descriptive models in Cox and Singer (1986). The worksheets are designed to be reproduced and used to score geologic descriptions of areas that may contain mineral occurrences, prospects, or deposits. The worksheets can be used to determine numerically the degree to which a given geologic description matches a particular model. If, after scoring, there is doubt about the choice of a particular model, reference can always be made to the original model contained in Cox and Singer (1986).

A WORKED EXAMPLE

To illustrate how a person might fill in a worksheet, the following example is taken from field observations and subsequent thin-section studies and geochemical analyses of a massive, quartz-rich, seriate to porphyritic Tertiary granite that occurs in the White Mountains of east-central Alaska (Weber and others, 1988). An earlier investigation (Dean Warner, written commun., 1984) suggested that the granite might be a host for Sn greisen deposits. With this in mind, the worksheet for the Sn greisen deposit model was filled in using the scores in table 2 based on the information that was available. The worksheet along with the scores of the attributes, is shown in table 3.

In the example, the age of the granite was established to be Tertiary and was considered to be the age of any mineralization that may have occurred. As a Tertiary age falls within the Phanerozoic age interval, a score of 100 is assigned to Phanerozoic on the worksheet.

Muscovite-leucogranite was identified as the major rock type present. On the worksheet, Muscovite-leucogranite is assigned a level of 3 for presence. Referring to table 2, the score that is associated with a level of 3 for RockTypes (Rk) is 45. Therefore, the score for Muscovite-leucogranite is 45. Taking note that Muscovite-leucogranite is a kind-of Leucogranite, Leucogranite is also present therefore. On the worksheet, Leucogranite is assigned a level of 4 for presence. Referring to table 2, the score that is associated with a level of 4 for Rk is 60, and therefore the score assigned to Leucogranite on the worksheet is 60. By similar reasoning, Granite and Felsic-plutonic RockTypes are also present, and by referring to table 2, they are each assigned the score of 75. The remaining RockType (Biotite-leucogranite) was missing—that is, neither its presence nor its absence could be confirmed. On the worksheet, Biotite-leucogranite is assigned a level of –2 for absence. As Biotite-leucogranite is considered missing rather than being absent, referring to table 2, the score associated with one level higher—that is, a level of –1—is –5, and therefore the score assigned to Biotite-leucogranite on the worksheet is –5.

In a similar way, scores were assigned to the remaining attributes under the different headings on the worksheet. Under each heading, the score assigned to each attribute was based on the score associated with the level specified for the attribute depending on whether the attribute was judged to be present, suspected to be present (present?), missing, or absent. Attributes whose presence-absence levels were not specified were assumed to be 2 and –2, respectively. Under headings for which there was no information available, (AssociatedDeposits, for instance, in this example), the score assigned to all of the attributes was 0.

When scores for all of the attributes were assigned, the partial scores—that is, the total scores under each heading—were calculated.

The total score in this example was 1,055 out of a possible maximum score of 2,930. Although this score is relatively low compared with the maximum score, scores for the four next highest scores among all of the other models obtained using Prospector II were 637 out of 2,430 for Sn veins, 576 out of 2,445 for Climax Mo, 559 out of 1,730 for Porphyry Sn, and 466 out of 1,795 for W veins. It should be noted that absolute rather than relative scores are used for ranking purposes. It was concluded that even though this area could not be considered a likely prospect for Sn greisen deposits, if deposits should exist, they most likely would be of this type rather than any other type.

This example brings out a problem that has persisted throughout the development of the models: the continuing confusion between regional and local characteristics. In performing regional mineral resource assessments, the scores obtained in applying the numerical models tend to be low, largely owing to the lack of information. At the same time, application of a particular model in an area in which the information is sufficient to conclude that, in all probability, one or more deposits of the type represented by the model do not exist results in large scores because the model, in detail, is not discriminating enough. Thus, even though such differences in scores that are obtained by application of the models in different areas are probably real and usable, reliance on absolute scores could lead to serious misinterpretation, and for this reason, caution is urged in applying the results indiscriminately.

TEST OF NUMERICAL MODELS

As a test of the numerical models, an experiment was performed that was designed to compare the results of classifying 124 lode deposits in Alaska by a panel of eight geologists using the Cox and Singer (1986) classification with the results obtained by classifying the same deposits using the numerical models. The 124 lode deposits were classified by the panel using the descriptions of the deposits given in Nokleberg and others (1987). Using the same descriptions, the 124 deposits were classified by Prospector II using the numerical models. The results of the experiment are summarized in table 4. The 124 deposits were classified by the panel of geologists into 27 different deposit types using the Cox and Singer classification. The five columns on the right in table 4 record the frequency of the rank order in which each of the 124 deposits was clas-

Model 15c

Worksheet for Numerical Model of Sn greisen deposits

Deposit, Prospect, or Occurrence: Cache Mountain
Location: White Mountains, East-Central Alaska
Description: Quartz-rich seriate porphyritic granite with ubiquitious miarolitic cavities and common occurrence of tourmaline.

AgeRange: Precambrian __ Phanerozoic 100
RockTypes: Felsic-plutonic (5 -5) 75 Granite (5 -5) 75 Leucogranite (4 -4) 60 Muscovite-leucogranite (3 -2) 45 Biotite-leucogranite (3 -2) -5
TextureStructure: Greisen ____ Veinlets ✔ Stockwork _____
Alteration: Greisenization (5 -2) -10 Albitization (5 -2) -10 Tourmalinization (3 -2) 200
Mineralogy: Cassiterite (4 -5) 60 Molybdenite (4 -5) -75 Arsenopyrite (3 -5) 30 Topaz (4 -2) 60 Tourmaline (4 -2) 60 Beryl (2 -4) 0 Wolframite (2 -3) -10 Bismuthinite (2 -2) -5 Fluorite (4 -3) 60 Calcite (1 -3) 15 Pyrite (2 -4) 30
GeochemicalSignature: Sn (4 -5) 60 F (5 -5) 75 B (5 -4) 75 Mo (2 -5) 0 Rb (2 -4) 0 Cs (2 -4) 0 Be (2 -3) 30 REE (2 -4) -30 U (2 -4) 30 Th (2 -4) 0 Nb (2 -4) 0 Ta (2 -4) 0 Li (2 -4) 0 W (2 -3) 30 As (2 -4) 0 Bi (2 -3) 30
GeophysicalSignature:
AssociatedDeposits: Sn greisen 0 Sn veins 0 Sn replacement 0
MaxScore: 2,930

Partial Scores

AgeRange: 100 **RockTypes:** 250 **TextureStructure:** 0 **Alteration:** 180
Mineralogy: 225 **GeochemicalSignature:** 300 **GeophysicalSignature:** 0
AssociatedDeposits: 0

Model Score: 1,055

sified using the numerical models. For example, of the six deposits classified by the panel as being a Gabbroic Ni-Cu deposit type, four of these were also classified as being a Gabbroic Ni-Cu deposit type by Prospector II. For the other two deposits, however, a Gabbroic Ni-Cu deposit type was Prospector II's third choice for one and fifth choice for the other. It should be noted that for both of these deposits, the panel had a question mark after their choice.

Table 4. Comparison of classification between Prospector II and panel of geologists using the Cox-Singer deposit classification for 124 metalliferous lode deposits in Alaska (Nokleberg and others, 1987)

[Alphanumeric characters in parentheses refer to model numbers in Cox and Singer (1986)]

Deposit type (classified by panel of geologists)	Frequency of ranking (classified by Prospector II) 1st	2nd	3rd	4th	5th
1. Gabbroic Ni-Cu deposits (7a)	4	0	1	0	1
2. Podiform chromite deposits (8a)	7	1	0	0	0
3. Serpentine-hosted asbestos deposits (8d)	1	0	0	0	0
4. Alaskan-PGE (9)	5	0	0	0	0
5. W skarn deposits (14a)	1	0	0	0	0
6. Sn skarn deposits (14b)	2	0	0	0	0
7. Sn vein deposits (15b)	1	0	1	0	0
8. Sn greisen deposis (15c)	1	0	0	0	0
9. Porphyry Cu deposits (17)	4	1	0	0	0
10. Cu skarn deposits (18b)	2	0	1	0	0
11. Zn-Pb skarn deposits (18c)	2	0	0	0	0
12. Fe skarn deposits (18d)	4	1	0	0	0
13. Porphyry Cu-Mo deposits (21a)	1	0	2	0	0
14. Porphyry Mo, low F deposits (21b)	1	0	0	0	0
15. Polymetallic vein deposits (22c)	14	3	0	0	0
16. Basaltic Cu deposits (23)	0	0	1	0	0
17. Cyprus massive sulfide deposits (24a)	0	0	1	0	0
18. Besshi massive sulfide deposits (24b)	3	0	0	0	0
19. Epithermal vein deposits (25b, 25c, 25d, 25e)	2	0	0	0	0
20. Hot-spring Hg deposits (27a)	3	1	0	0	0
21. Sb-Au vein deposits (27d, 27e)	5	0	0	0	0
22. Kuroko massive sulfide deposits (28a)	9	0	0	0	0
23. Sandstone U deposits (30c)	1	0	0	0	0
24. Sedimentary exhalative Zn-Pb deposits (31a)	2	0	0	0	0
25. Bedded barite deposits (31b)	2	0	0	0	0
26. Kipushi Cu-Pb-Zn deposits (32c)	1	0	0	0	0
27. Low-sulfide Au quartz vein deposits (36a)	25	1	0	0	0
Totals	103	8	7	0	1

Of the 124 deposits classified by the panel, 103 of these were classified the same by Prospector II. This represents an 83 percent agreement between the two sets of classifications. The deposit types for which there was perfect agreement between the two were Serpentine-hosted asbestos, Alaskan-PGE, W skarn, Sn skarn, Sn greisen, Zn-Pb skarn, Porphyry Mo–low F, Besshi massive sulfide, Epithermal vein, Sb-Au vein, Kuroko massive sulfide, Sandstone U, Sedimentary exhalative Zn-Pb, Bedded barite, and Kipushi Cu-Pb-Zn. In almost all cases, the deposit type receiving the highest score was clearly distinguishable from the other deposit types, which received considerably lower scores. There were 8 deposits for which the classification made by the panel was Prospector II's second choice. For 5 of these deposits, the panel either put a question mark after their choice or else suggested that the deposit could be considered one of two different deposit types. Such ambiguity highlights the fact that the classification of a deposit often is largely a matter of judgment. The scores obtained using Prospector II for each of the 9 deposits characteristically were not markedly different for the first and second choices. By combining Prospector II's first and second choices as indicating a match with the classification made by the panel, there was agreement in 111 out of the 119 deposits classified—that is, a 93 percent agreement.

The deposit for which there was the most disagreement between the panel and Prospector II was the Spirit Mountain deposit (Nokleberg and others, 1987, p. 87). The panel classified this deposit as a Gabbroic Ni-Cu deposit type with a question mark, whereas Prospector II classified the deposit unequivocally as a Dunitic Ni-Cu deposit type (Cox and Singer, 1986, p. 24). The deposit is described as disseminations of sulfides in serpentinized peridotite and pyroxenite that are associated with gabbroic sills that have intruded upper Paleozoic limestones. The ore minerals contain Ni and Cu. This description fits closely with the Dunitic Ni-Cu deposit model described as disseminated sulfide mineralization in intrusive dunites and olivine peridotites that exhibit prograde and retrograde serpentinization. Although the description of the Gabbroic Ni-Cu deposit model is similar, what is lacking in the model is any mention of serpentinization. This attribute was critical in this instance. The three other deposit models that Prospector II rated higher than the Gabbroic Ni-Cu deposit model were the Alaskan-PGE, Podiform chromite, and Serpentine-hosted asbestos deposit models. In order to resolve all the differences in the classification of this particular deposit, it would be necessary to review the description again with the panel members and compare it with the descriptions of these five models.

A different situation exists for the Bernard Mountain deposit (Nokleberg and others, 1987, p. 55), in which the panel members classified the deposit as a Podiform chromite deposit type, whereas Prospector II narrowly classified the deposit as a Bushveld-Cr deposit type. The score for the Bushveld-Cr deposit model was 380 out of a possible 1,705, whereas the score for the Podiform chromite deposit model was 360 out of a possible 1,325. Situated in between these two models, were the scores for the Alaskan-PGE and the Merensky-Reef-PGE deposit models, which were 370 out of a possible 1,925 and 365 out of a possible 1,750, respectively. The relatively low scores obtained for all four of the models suggest that it may not be possible with the present information to distinguish among them.

CONCLUSIONS

Numerical mineral deposit models demonstrate the technical feasibility of encoding descriptive mineral deposit models to provide (1) a numerical-based consultant for regional mineral resource assessments, (2) objective evaluations of particular geologic settings as part of regional assessments, and (3) determination of the most likely model or models that best match a particular geologic setting. This approach is potentially valuable for (1) screening data bases of mineral occurrences, (2) providing instruction about the geology of mineral deposits, (3) systematizing the development of mineral deposit models, and (4) introducing objective procedures for evaluating models numerically.

While these numerical deposit models have useful applications in their present form, the extent to which their potential can be realized will depend upon future activities, some of which are already in progress. First, it is clear that the numerical models cannot be better than the descriptive models upon which they are based. The 87 numerical models represent but a sampling of what is ultimately desirable. Moreover, only a few of the numerical models have been completely tested and calibrated for regional mineral resource assessments. Many years will be required to develop numerical models for all types of deposits of economic interest, and refining these models and introducing new models as new deposit types are identified will be a continuing task. Fortunately, the formats that have been developed for the descriptive models will make it easier to carry out this task.

Because the techniques used to develop numerical models are new, few geologists are familiar with them. As the advantages of this numerical approach become more widely appreciated, more geologists will be interested in becoming involved in this activity. Several activities could encourage their participation, including (1) further exposure of these ideas at professional conferences and workshops, (2) acceptance of the publication of such models as a significant professional activity, (3) incorporation of these ideas in a course on economic geology, and (4) provision of ways for geologists in the governmental, academic, and industrial communities to access the models by computer.