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Characteristic Analysis—1981: Final Program and a Possible Discovery[1]

Richard B. McCammon,[2] Joseph M. Botbol,[3] Richard Sinding-Larsen,[4] and Roger W. Bowen[2]

The latest or newest version of the characteristic analysis (NCHARAN) computer program offers the exploration geologist a wide variety of options for integrating regionalized multivariate data. The options include the selection of regional cells for characterizing deposit models, the selection of variables that constitute the models, and the choice of logical combinations of variables that best represent these models. Moreover, the program provides for the display of results which, in turn, makes possible review, reselection, and refinement of a model. Most important, the performance of the above-mentioned steps in an interactive computing mode can result in a timely and meaningful interpretation of the data available to the exploration geologist. The most recent application of characteristic analysis has resulted in the possible discovery of economic sulfide mineralization in the Grong area in central Norway. Exploration data for 27 geophysical, geological, and geochemical variables were used to construct a mineralized and a lithogeochemical model for an area that contained a known massive sulfide deposit. The models were applied to exploration data collected from the Gjersvik area in the Grong mining district and resulted in the identification of two localities of possible mineralization. Detailed field examination revealed the presence of a sulfide vein system and a partially inverted stratigraphic sequence indicating the possible presence of a massive sulfide deposit at depth.

KEY WORDS: Grong, Norway, sulfide mineralization, ternary variables.

INTRODUCTION

Characteristic analysis is a multivariate technique that has been used successfully in identifying exploration targets for a wide variety of deposit types (Botbol, Sinding-Larsen, McCammon, and Gott, 1978; Sinding-Larsen, Botbol, and McCammon, 1979; McCammon, Botbol, McCarthy, and Gott, 1979; Sinding-Larsen and Strand, 1981). It was devised originally as a method for interpreting

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[2]U.S. Geological Survey, Reston, Virginia.
[3]U.S. Geological Survey, Woods Hole, Massachusetts.
[4]Norwegian Institute of Technology, Trondheim, Norway.

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regionalized multivariate data in geology, geochemistry, and geophysics. To date, it has been applied mainly in the search for deposits that are either poorly exposed or concealed in some way.

The newest version of the characteristic analysis (NCHARAN) computer program includes options for the selection of regional cells for characterizing deposit models, the selection of variables that constitute the models and the choice of logical combinations of variables that best represent these models. Moreover, the program provides for the display of results and thus makes possible review, reselection, and refinement of a model. Most important, the performance of the above-mentioned steps in an interactive computing mode can result in a timely and meaningful interpretation of the data avilable to the exploration geologist.

The purpose of this paper is to present improvements in the method and to describe the latest application, which involves the possible discovery of a massive sulfide deposit in Norway. The background of the method and previous applications can be found in the papers cited above.

DATA TRANSFORMATION

In earlier applications, the data used in characteristic analysis were transformed into binary form by assigning the value of 1, meaning favorable, or the value of 0, meaning unfavorable or unevaluated. In order that the two states represented by the value 0 could be distinguishable, the data now are transformed into ternary form by assigning the value of 1 meaning favorable as before, the value of −1 meaning unfavorable, and the value of 0 meaning unevaluated. The reason for using the ternary representation of the data is that in many instances the explorationist can judge areas as being unfavorable with respect to particular variables. Thus, for a given exploration model, the researcher assumes that in characteristic analysis, the value +1, 0, or −1 can be assigned to each of the variables for each location (cell) for which data are available. If data are missing, no assignment is made.

The data for each variable are transformed into ternary form prior to characteristic analysis of any area that has been divided into regional cells. The manner in which this transformation is performed is not prescribed, however. It depends upon the nature of the exploration model and the nature of the data. For geochemical data, favorability is strongly indicated by local anomalies deduced from second derivative surfaces. For geophysical data, on the other hand, favorability is indicated and assigned on the basis of regional gradients, local increases or decreases in measured values, and recognition of special features on regional contour maps. For geologic map data, the presence of a particular rock type could be a favorable criterion. To a large extent, the success or failure of characteristic analysis of a given set of data rests upon the ability of the interpreter to determine what consistutes favorability for each variable.

LOGICAL COMBINATIONS OF TRANSFORMED VARIABLES

In exploration, an observation or measurement of a single variable is rarely sufficient to detect the presence of a concealed deposit. More often, a combination of observations or measurements of several variables is significant in terms of predicting the presence (or absence) of a deposit. In the earlier formulation of characteristic analysis, the favorability f of a given cell was defined as a weighted linear combination of the binary-transformed variables, that is

$$f = a_1 x_1 + a_2 x_2 + \cdots + a_n x_n \quad (1)$$

where the a_i ($i = 1, 2, \ldots, n$) represented the weights and the x_i ($i = 1, 2, \ldots, n$) represented n transformed variables. In other words, once the variables were transformed, they were combined in an additive expression. No provision was made for other kinds of combinations. However, an experienced explorationist commonly has prior knowledge of different combinations of variables that are judged to be favorable (or unfavorable) with respect to particular models. The most common combinations are logical ones, that is, AND, OR, and NOT combinations. Consequently, the x_is in (1) have been extended to include not only ternary-transformed variables but also logical combinations of ternary-transformed variables. To accomplish this extension, a truth table was devised for ternary-transformed variables (Table 1). The table defines the values of all logical combinations of two ternary-transformed variables, consistent with the rules of logical operations.

Once the logical operations are defined for two ternary-transformed variables, more complex logical expressions can be evaluated. For instance, the logical expression defined for three variables A, B, and C, as

$$(A \text{ OR } B) \text{ AND } (\text{NOT } C)$$

Table 1. Truth Table for Ternary-Valued Variables A and B[a]

A	B	A OR B	A AND B	NOT A
1	1	1	1	−1
1	0	1	0	−1
1	−1	1	−1	−1
0	1	1	0	0
0	0	0	0	0
0	−1	0	−1	0
−1	1	1	−1	1
−1	0	0	−1	1
−1	−1	−1	−1	1

[a]The numbers 1, −1, and 0 represent favorable, unfavorable, and unevaluated states of nature, respectively, with respect to a given deposit model.

can be evaluated using Table 1 by evaluating

$$D = A \text{ OR } B$$

$$E = \text{NOT } C \qquad \text{and}$$

$$D \text{ AND } E$$

The capacity to construct logical combinations of ternary-transformed variables enhances the results obtained by using characteristic analysis. The value of such logical combinations is demonstrated in the application described later in this paper.

MODEL GENERALIZATION

Most models used in exploration are based primarily on observations or measurements taken in and around known deposits. It is presumed that similar observations or measurements in unknown areas are likely to reflect undiscovered deposits and, therefore, are likely to be clues to favorable target areas. The degree of match between a set of observations or measurements in an unknown area and the observations or measurements that define a model forms the basis of "characteristic analysis." As noted, a model is generally defined by a selected set of ternary-transformed variables in areas of known deposits.

The weights, a_i, in (1) are determined by solving the matrix equation

$$(X'X)\,\mathbf{a} = \lambda\mathbf{a} \tag{2}$$

where λ is the largest eigenvalue of $(X'X)$. X is the $m \times n$ matrix of observations of n ternary-transformed variables (or combinations) for m selected cells that comprise the model. The a_is are the elements of the eigenvector $\mathbf{a}$ associated with λ and are scaled such that f in (1) lies between -1 and $+1$. The solution in (2) is equivalent to maximizing

$$\sum_{i=1}^{n} \frac{\mathbf{f}'\mathbf{x}_i}{\mathbf{f}'\mathbf{f}} \tag{3}$$

The maximized value is a measure of the overall similarity of the expression in (1) to the values for the ternary-transformed variables in the model.

For a cell outside the model area, the favorability is determined using (1). Values of f close to 1 indicate high degrees of match with the model and hence are judged to be highly favorable. Values of f close to -1 indicate a low degree of match with the model and hence are judged to be unfavorable. Values of f close to zero indicate neither a high degree nor a low degree of match, and consequently, are judged to be neutral.

A problem that arises in model definition is cell selection. Most often, the cells selected are those that contain deposits of the type being considered. Because a deposit usually has unique features, the data used to define a model are overly restrictive in the sense that data from other areas are unlikely to match them closely. Consequently, a model should be generalized by the inclusion of regional cells that do not contain deposits.

The following is a procedure whereby generalized models can be constructed. Consider k cells that contain deposits. For n ternary-transformed variables, a model can be defined using (2). Suppose now that (1) is applied to other cells within a larger area and that l of these cells are determined to have the same or a greater degree of match with the existing model than the k cells have. A question that can be asked is whether this degree of match is due purely to chance or whether a significant relation exists between these cells and the cells that comprise the model. The question can be answered by considering the matches among the ternary-transformed variables for the $k + l$ cells. For each such variable, the value is 1, 0, or -1. Thus, for each variable for $k + l$ cells, there is an ordered array of $k + l$ 1's, 0's, or -1's, for example, $\{1, 1, 0, -1, \ldots, 1\}$. For two variables expressed as vectors $\mathbf{u}$ and $\mathbf{v}$, the number of nonzero matches m can be expressed as

$$m = \mathbf{u}'\mathbf{v}. \tag{4}$$

If the assumption is made that the observed sequences of values contained in $\mathbf{u}$ and $\mathbf{v}$ could have occurred in any order, it is possible to determine the probability that the observed number of matches is not a chance occurrence (the expression for this probability is given in the Appendix). If this probability is high, the two variables have highly similar patterns of occurrence (or nonoccurrence). If the probability is low, the two variables have highly dissimilar patterns of occurrence (or nonoccurrence). Consider now an $n \times n$ symmetric matrix P that contains these probabilities and that contains unity along the main diagonal. P can now be substituted for $X'X$ in (2), and a set of weights, a_is, can be calculated. The degree of match f is calculated for the $k + l$ cells, and those p cells having the highest values are selected as the cells of a generalized model. In this way, a model is defined that is not restricted in its application by the unique features of deposits in an area.

A POSSIBLE DISCOVERY

In January 1978, the Grong Mining Company had accumulated more than 10 years of exploration data in the Grong mining district in central Norway (inset, Fig. 1). The data included more than 14,000 stream-sediment samples analyzed for trace metals, electromagnetic and magnetic measurements taken from helicopter surveys over the area at a scale of 1 : 20,000, and a recently compiled geologic map of the area at a scale of 1 : 50,000. Because their concession in the Grong area was to be terminated in 1982, they decided to undertake a comprehensive review of all the existing data in order to determine what followup exploration might be performed prior to the termination date. In June 1978, the company decided that characteristic analysis would be applied to the data in an attempt to delineate new areas favorable for massive sulfide deposits.

The first recorded sulfide discovery in the Grong area was made in 1873 (Reinsbakken, 1980). An intensive exploration program was conducted from 1913 to 1916 and again from 1935 to 1938. From 1965 to the present, exploration has been practically continuous. To date, three large and several small massive sulfide deposits have been discovered in the area (Bjorlykke, Grenne, Rui, and Vokes, 1980). Because of the complexity of the geologic setting, however, and the wealth of new data that have recently become available, the possibility of finding additional deposits is considered good.

A simplified geologic map of the Grong district is shown in Fig. 1. The

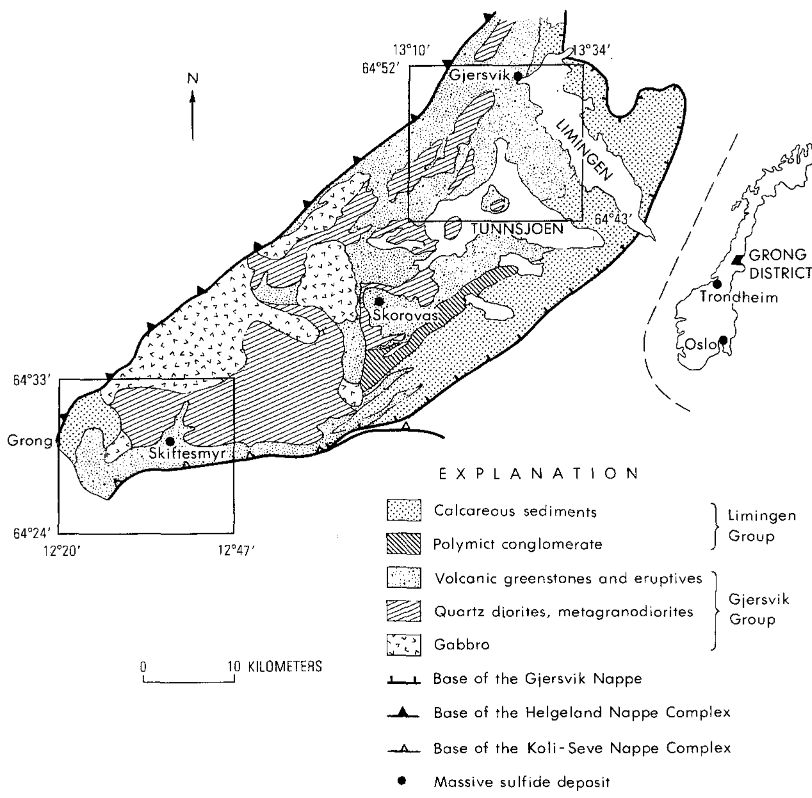


Fig. 1. Simplified geologic map of the Grong district Norway, modified from Lutro (1979). The study area containing the Skiftesmyr deposit and the Gjersvik area, which is to be evaluated, are outlined.

major unit in the area is the Gjersvik Nappe, which consists of a thick sequence of greenstones overlain by sandy and conglomeratic flysch-type rocks (Oftedahl, 1980). The greenstones, chiefly of the island arc type, are mostly pillow lavas with which lenses of sulfide may be associated. Sulfide mineralization, however, is more closely associated with acidic, keratophyric tuffs and lavas, agglomerates, and jasper, or chert containing magnetite (Kollung, 1979).

To apply characteristic analysis to the exploration data, it was necessary to divide the area of interest into regional cells and to assign each cell a value +1, 0, or −1 for each variable. Cells having no data or cells outside the area of interest were left blank. In the present application, a value of +1 was used to indicate that a measurement or observation within a cell or a value extrapolated from adjacent cells was favorable with respect to mineralization. A value of −1 was used to indicate that an observation or measurement was unfavorable, and a value of 0 was used to indicate that favorability could not be determined.

The exploration data for the Gjersvik Nappe were coded into 5000 regional cells measuring 500 m on a side. In this paper, two areas containing 1200 of the 5000 regional cells have been considered (Fig. 1). Of the more than 150 variables initially coded for each cell and evaluated in terms of relevance for evaluating the favorability of occurrence of sulfide mineralization, only 27 variables, 11 of them geophysical, 3 geological, and 13 geochemical were finally selected and used in the characteristic analysis (Table 2). Contour maps of the geophysical data were considered as surfaces and were analyzed in terms of their morphology. For instance, a magnetic isogam map within a given cell was examined to see whether a plateau, slope, valley, peak, or ridge was present in the contour pattern. Local changes in these features were coded. The geological map data were transformed into ternary form by noting the presence or absence of the three main rock types exclusive of intrusive rocks in the area. Geochemical variables were coded by transforming the data to reflect the presence or absence of anomalies relative to threshold values. The 27 transformed variables were the variables used to construct the models for characteristic analysis.

Mineralized Model

Three large and several small massive sulfide deposits have been found in the Grong district. In defining a model, it was necessary to consider which of these deposits occurs in a geological environment similar to the environment of the larger Gjersvik area which was to be evaluated. The geologic setting rather than the size of deposit was considered a critical factor. Thus, the small Skiftesmyr deposit in the southern part of the Grong district was judged to occur in a setting most similar to that of the Gjersvik area as a whole. This deposit occurs in a greenstone unit within the Gjersvik Group. The greenstone is mostly a pillow lava, and the sulfide mineralization is closely associated with acidic, keratophyric tuffs and lavas.

Table 2. Variables Used to Describe Exploration Data on the Grong District, Norway

Variables	Description
Magnetic variables	
MA 1	Regional magnetic gradient
MA 2	Local decrease in regional magnetic gradient
MA 3	Local increase in regional magntic gradient
MA 4	Local magnetic peak
MA 5	Joint presence of MA 1 as well as either MA 3 and/or MA 4
Electromagnetic variables	
IM 6	Imaginary anomaly
IM 7	Local imaginary anomaly or anomaly peak on a regional anomaly zone
LE 8	Estimate of conductivity calculated
RE 9	Absence of either a positive or negative real anomaly in the cell and adjacent cells
RE 10	Negative real anomaly in cell and adjacent cell
RE 11	Positive real anomaly in cell and adjacent cell
Geological variables	
FIN	A tuffaceous-sedimentary sequence consisting of green schist, calcareous schist, phyllites, thin lavas, keratophyres, quartzites, and a persistent limestone
KER	Quartz keratophyre
GRO	Several greenstone units. The older greenstone is characterized by a marked banded structure. The middle greenstone is typically fine grained, dark green, and massive to moderately schistose, and magnetite and pyrite are common. The younger greenstone is somewhat lighter and coarser grained than the middle greenstone and has little or no magnetite and pyrite.
Geochemical variables	
Cu, Pb, Zn, Ni, Cd, Ag	A cell is anomalous for one of the elements if its concentration in one of the cell samples deviates significantly from the geochemical background defined as the average value of the concentration of the lowest samples in the eight adjacent cells.
Cu/Ni, Pb/Ni, Zn/Ni, Cu/Zn, Pb/Zn, Zn/Mn, Zn/V	Ratios between the deviations from background for selected elements

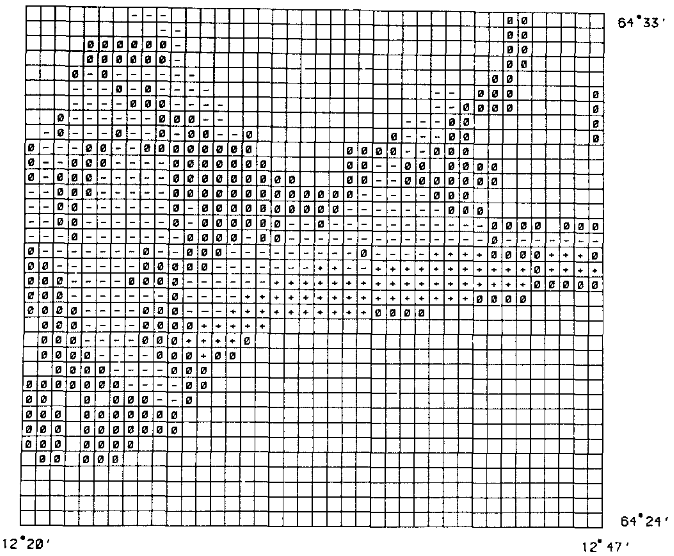
Underlying the greenstone is a tuffaceous-sedimentary sequence consisting of greenschist, calcareous schist, phyllite, thin metavolcanic flow rocks, quartzites, and a persistent limestone. From available evidence, this sequence can not be considered favorable for sulfide mineralization. Therefore, types in and around the Skiftesmyr deposit considered part of any mineralized model are delineated.

Figure 2A is a map of the area of the Skiftesmyr deposit which shows the distribution of cells in which the tuffaceous-sedimentary sequence is present ("+"), absent ("–"), or unevaluated ("0"). The blank cells represent areas underlain by units not part of the Gjersvik group. If all cells from which the tuffaceous-sedimentary sequence is absent are considered to be underlain either by greenstone or quartz keratophyre, such cells potentially could be part of a model. The cells for which greenstone or quartz keratophyre is present are shown in Fig. 2B. All other cells are eliminated from further consideration.

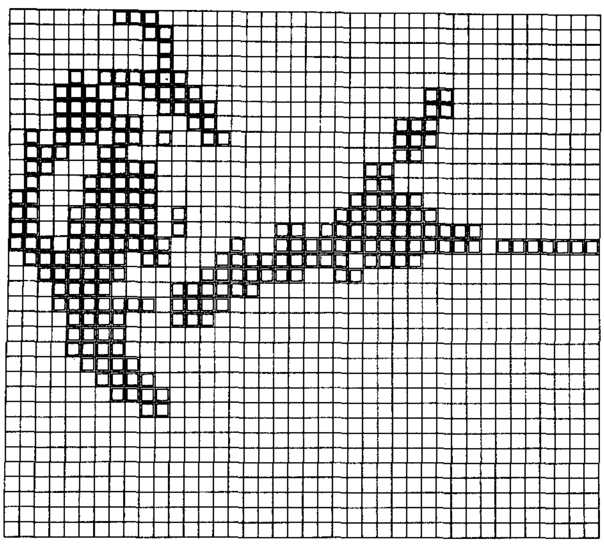
An initial mineralized model was defined by considering only the cells that contain the Skiftesmyr deposit. They are shown in Fig. 2C. Thus, the known mineralization is contained within an area of 1000 by 500 m. For the variables of interest, we calculated the characteristic weights for the two cells that comprised the initial model called M1. The weights rounded to the nearest hundredths are listed in Table 3. By use of these weights, the degree of match for each cell in Fig. 2B was calculated. The frequency distribution of the degree of match is given in Table 4. For purposes of graphic display, the degrees of match were grouped into classes corresponding to the perceived modes in the frequency distribution. The degree of match is represented in Fig. 2D for classes numbered from 1 to 6 in which class 1 represents the mode for the lowest degree of match and class 6 represents the mode for the highest degree of match. The procedure is used throughout this paper to represent the degree of match in graphic form.

As stated above, models based solely on cells that contain known mineralization may not be optimal in that such models are overly restrictive in their application in other areas. Thus, the model should include other cells that are similar to cells in the model but that may or may not contain mineralization. We expanded the model M1 by including all cells in Fig. 2D in which the degree of match is in class 4 or greater. The cells for which this is true are shown in Fig. 2E and constitute what can be considered as a provisional generalized mineralized model called M2, which includes the two cells containing the deposit.

The problem now is that we may have overgeneralized the model by including cells in which the variables are unrelated. Unrelated cells are detrimental and, therefore, should be eliminated. To identify unrelated cells, we calculated the characteristic weights for the variables of interest based on the probability matrix described above. These weights are given in Table 3. Using the weights, the degree of match for each cell in Fig. 2B is calculated (see Fig. 2F). The classes for the degree of match range from class 1 to class 4. The highest class, class 4, is associated with the two cells in which the deposit occurs. Thus, cells in class 4 were retained and formed the basis of a generalized model. The cells ultimately kept as model M3 are shown in Fig. 2G. To summarize, an initial model of two cells was expanded to a model of 58 cells and finally contracted to a model

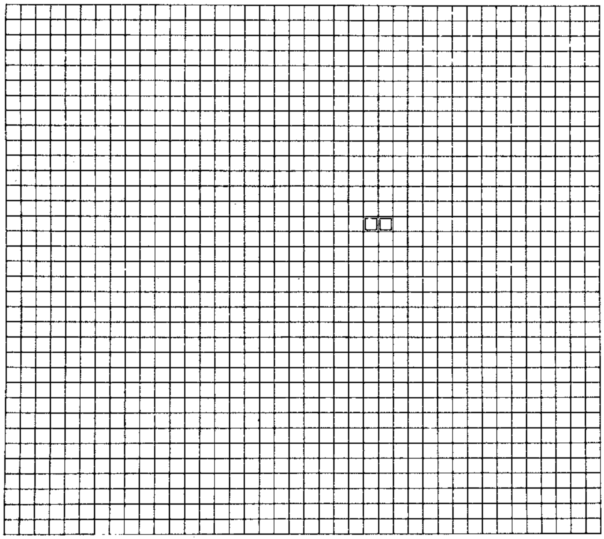


(A)

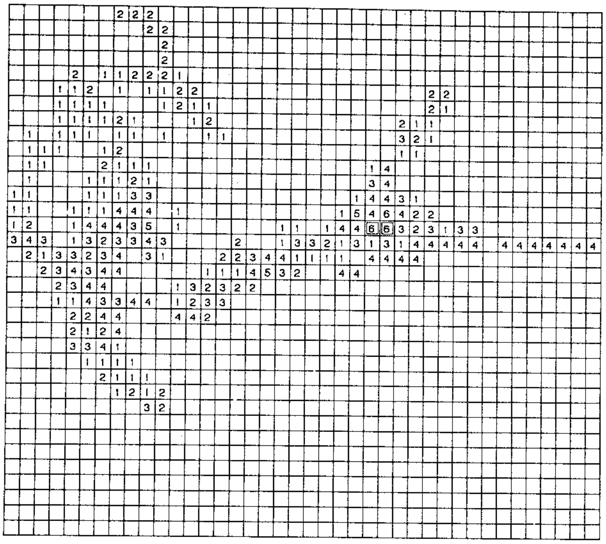


(B)

Fig. 2. Plan maps of the study area containing the Skiftesmyr deposit illustrating steps in construction of the mineralized models. Each cell in the study areas measure 500 m on a side. (A) Plan map showing areal distribution of an unfavorable tuffaceous-sedimentary sequence. Presence is indicated by a plus sign, absence by a minus sign, and lack of evaluation, by a zero. The blank cells represent areas underlain by units not part of the Gjersvik Group. (B) Plan map of outlined cells from which the unfavorable tuffaceous-sedimentary

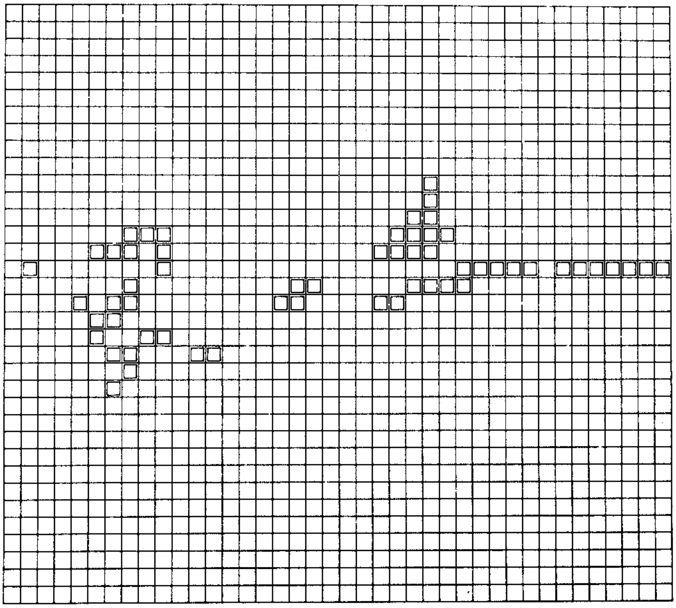


(C)

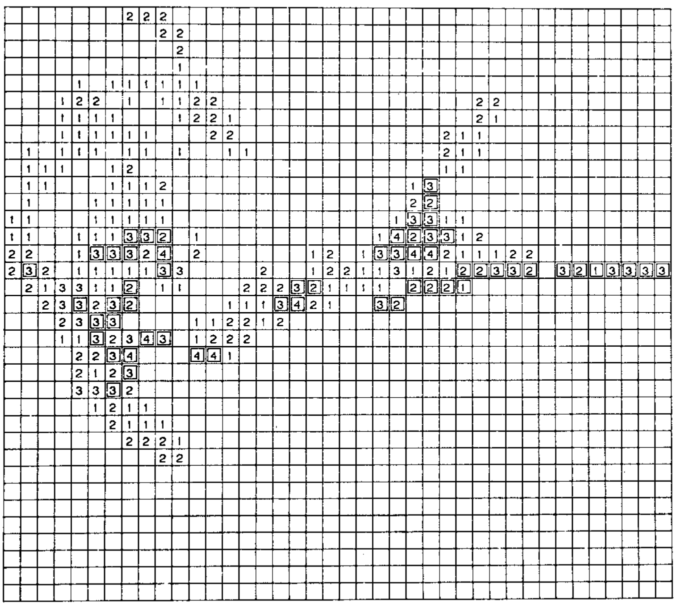


(D)

sequence is absent. These cells contain either greenstone or quartz keratophyre or both (C). Plan map showing the two cells containing the Skiftesmyr deposit and comprising model M1. (D) Plan map of the degree of match of cells outlined in B with the mineralized model M1. The cell values correspond to degrees of match from the lowest which is 1 to the highest which is 6. (E) Plan map shows by outlining the cells in D having values of 4 or greater and comprising model M2. (F) Plan map of the degree of match of cells outlined

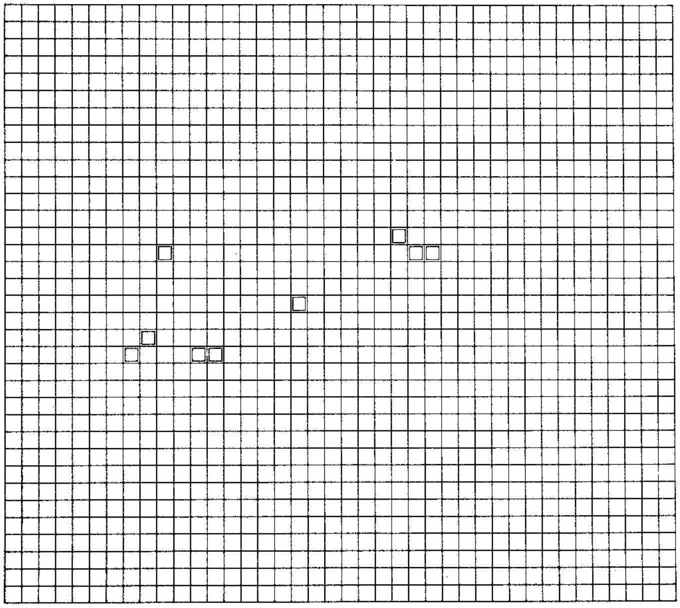


(E)

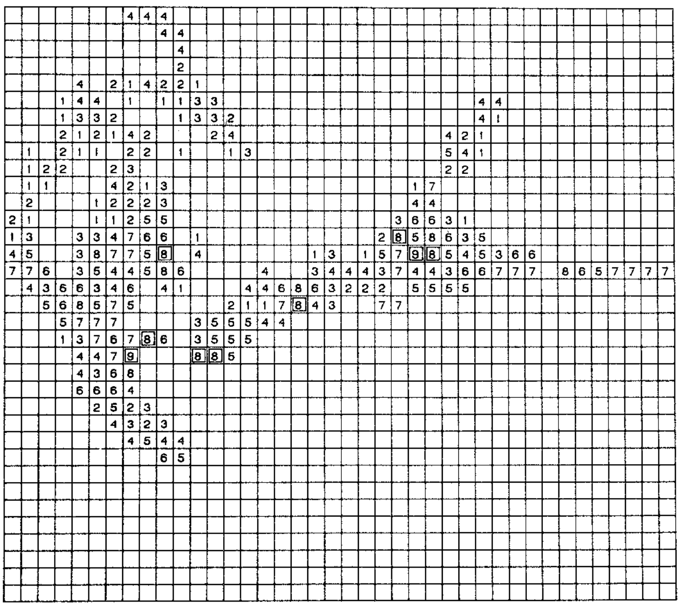


(F)

in B with the mineralized model M2 based on characteristic weights calculated from the probability matrix for the outlined cells in E. The cell values correspond to the degrees of match from the lowest which is class 1 to the highest which is class 4. (G) Plan map shows by outlining the cells in F having values equal to 4 and comprising model M3. (H) Plan



(G)



(H)

map of the degree of match of cells outlined in B with the mineralized model M3 based on characteristic weights calculated from the product matrix for the outlined cells in G. The cell values correspond to degrees of match from the lowest, which is class 1, to the highest which is class 9.

Table 3. Characteristic Weights of Variables in the Mineralized and Lithogeochemical Models for the Skiftesmyr, Norway Area[a]

	Mineralized models			Lithogeochemical models	
	M1	M2	M3	L1	L2
Number of cells	2	58	9	44	5
Variables					
MA 1	.23	.17	.28	.24	.26
MA 2	.23	.18	.28	.22	.26
MA 3	.23	.17	.22	.22	.16
MA 4	.23	.15	.16	.25	.26
MA 5	.23	.17	.03	.23	.26
IM 6	.23	.18	.28	.23	.26
IM 7	.23	.19	.28	.24	.26
LE 8	.23	.15	.09	.25	.26
RE 9	.23	.20	.28	.23	.26
RE 10	.23	.18	.28	.22	.26
RE 11	.23	.16	.28	.23	.26
KER	.23	.19	–	.22	.16
GRO	.23	.18	.28	.14	.26
Ni	–.12	.25	.12	.18	–
Cd	–.12	.26	.06	.14	–
Ag	.23	.24	.13	.16	.07
Cu/Ni AND Cu	.23	.26	.28	.24	.21
Cu/Zn AND Cu	.23	.25	.22	.22	.16
Pb/Ni AND Pb	.23	.22	.09	.12	.21
Pb/Zn AND Pb	.23	.21	.12	.16	.21
Zn/Ni AND Zn	.12	.24	.19	.19	.11
Zn/Mn AND Zn	.12	.25	.22	.21	.16
Zn/V AND Zn	.12	.25	.19	.19	.11

[a]The weights for M1, M3, and L2 were calculated from a product matrix, and those for M2 and L1 were calculated from a probability matrix.

of nine cells. The tasks remaining were the final selection of variables and the calculation of weights. For the variables of interest, the characteristic weights were calculated from the product matrix derived from the model that consisted of the cells in Fig. 2G. Variables having negative weights were removed from consideration and the weights of the retained variables recalculated. The weights are given in Table 3 and represent a generalized mineralized model. As a check, the degree of match for each cell in Fig. 2B was calculated with respect to the model. The classes range from class 1 to class 9 and are shown Fig. 2H. The model is comprised of cells in the two highest classes and is dissimilar to cells not part of the model. The generalized model can be interpreted as being representative of the geologic setting associated with sulfide mineralization and can be regarded as a model for exploration in areas in which similar geologic settings exist.

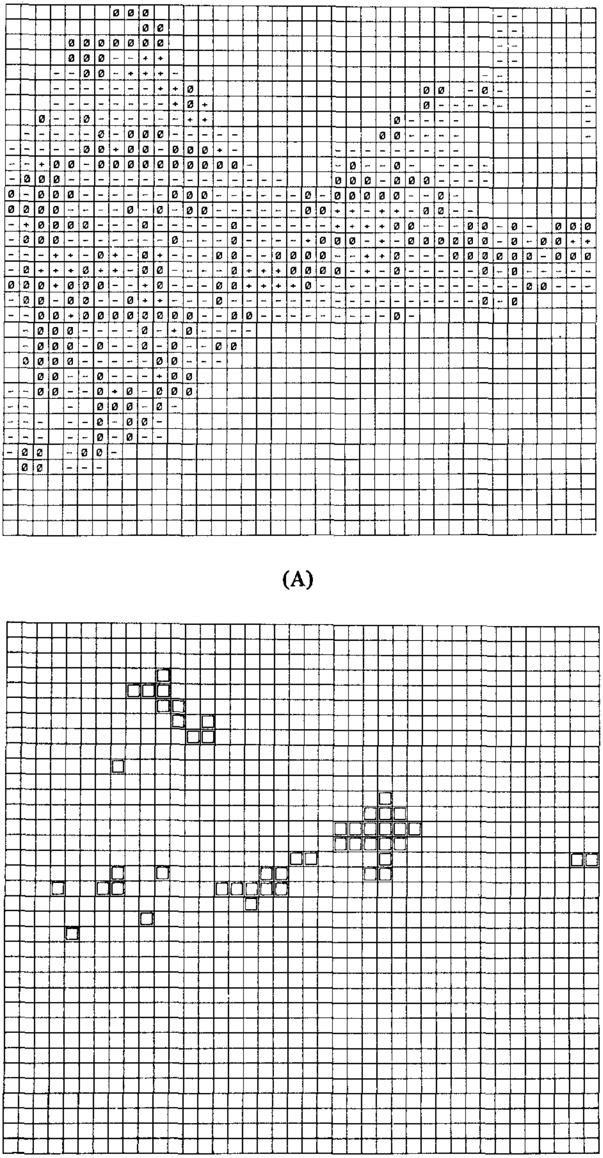
Lithogeochemical Model

A different approach in the construction of a model involves combining regional characteristics associated with known mineralization. As noted above, the massive sulfide deposits in the Grong region are contained within the greenstone units and are associated with quartz keratophyre. In addition, the Skiftesmyr deposit and others contain trace amounts of lead (Bjorlykke and others, 1980). On this basis, a single logical variable was defined which combined these

Table 4. Frequency Distribution of the Degree of Match for Cells Outlined in Fig. 2B Based on Characteristic Weights for Mineralized Model M1[a]

	Class interval		Model cells–frequency	Nonmodel cells–frequency	Class
1	-0.66	-0.59	0	2	
2	-0.59	-0.51	0	1	
3	-0.51	-0.44	0	3	
4	-0.44	-0.37	0	9	
5	-0.37	-0.30	0	12	1
6	-0.30	-0.23	0	20	
7	-0.23	-0.15	0	17	
8	-0.15	-0.08	0	37	–
9	-0.08	-0.01	0	19	
10	-0.01	0.06	0	33	2
11	0.06	0.13	0	16	–
12	0.13	0.21	0	22	3
13	0.21	0.28	0	17	–
14	0.28	0.35	0	12	
15	0.35	0.42	0	11	4
16	0.42	0.50	0	5	
17	0.50	0.57	0	7	–
18	0.57	0.64	0	1	5
19	0.64	0.71	0	2	–
20	0.71	0.78	0	1	
21	0.78	0.86	0	0	
22	0.86	0.93	1	0	6
23	0.93	1.00	1	0	
	Totals		2	247	

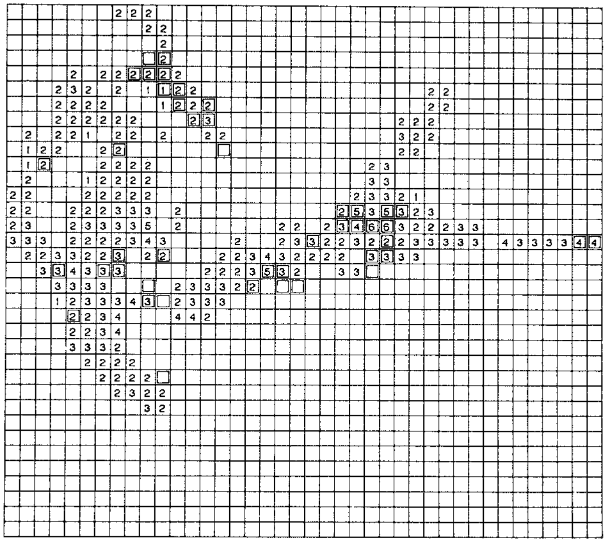
[a]The degree of match is expressed as a score which ranges from −0.66 to +1. The scores are grouped in 23 equal class intervals of approximately .07 and these in turn are grouped into classes that correspond to the modes perceived in the distribution.



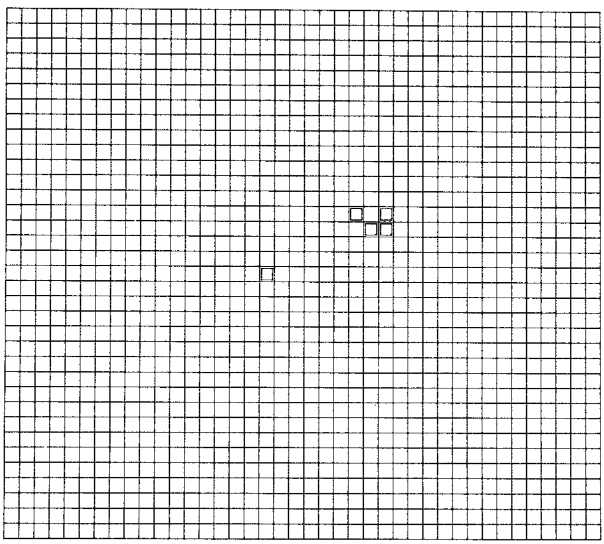
(A)

(B)

Fig. 3. Plan maps of the study area containing the Skiftesmyr deposit illustrating the steps in the construction of the lithogeochemical models. Each cell in the study area measures 500 m on a side. (A) Plan map showing the areal distribution of the logical variable (GRO · OR·KER)·AND·Pb for which GRO, KER, and Pb are defined in Table 2. The plus sign indicates presence, the minus sign indicates absence, and the zero indicates that the variable

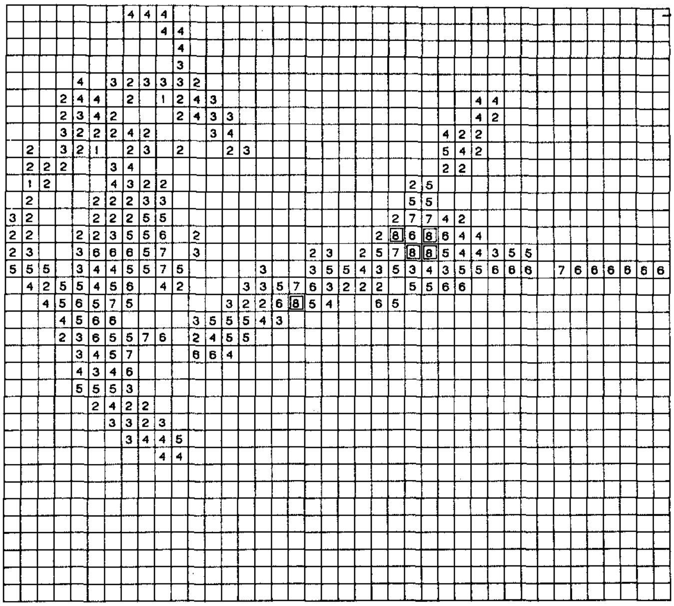


(C)



(D)

cannot be evaluated. (B) Plan map of outlined cells marked by a plus sign in A. These cells comprise model L1. (C) Plan map of degree of match of cells outlined in Fig. 2B with lithogeochemical model L1 based on characteristic weights calculated from probability matrix for the outlined cells in B. The cell values correspond to degrees of match from lowest which is class 1, to highest, which is class 6, (D) Plan map showing by outlining the cells in



(E)

C having values of 5 or 6. These cells comprise model L2. (E) Plan map of degree of match of cells outlined in Fig. 2B with lithogeochemical and L2 based on characteristic weights calculated from product matrix for the outlined cells in D. The cell values correspond to degrees of match from lowest, which is class 1, to highest, which is class 8.

characteristics as

$$(\text{GRO}\cdot\text{OR}\cdot\text{KER})\cdot\text{AND}\cdot\text{Pb} \qquad (5)$$

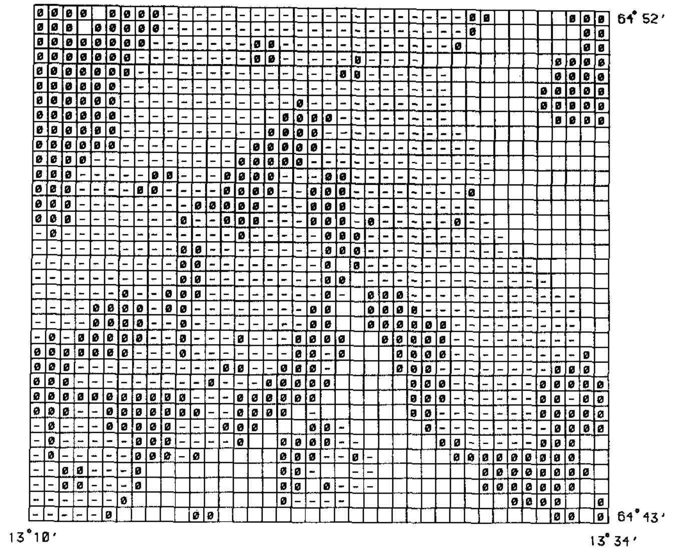
where GRO is greenstone, KER is quartz keratophyre, and Pb represents an anomalous concentration of lead. A map of this variable is shown in Fig. 3A for the area in the vicinity of the Skiftesmyr deposit. For each cell, a plus sign indicates the presence of either greenstone or quartz keratophyre and an anomalous concentration of lead, a minus sign indicates the complement, and a zero indicates that the combined presence cannot be evaluated. All cells marked by a plus sign in Fig. 3A are outlined in Fig. 3B and define a provisional generalized lithogeochemical model, L1. Comparison of Fig. 3B with Fig. 2C reveals that the two cells that contain the Skiftesmyr deposit are part of L1.

The cells in Fig. 3B were selected on the basis of three variables (GRO, KER, and Pb). Probably other variables need to be considered if the model is to be useful in delineating favorable ground outside the area surrounding the Skiftesmyr deposit. Moreover, restricting attention to only three variables results in the inclusion of too many cells and thus making the model too generalized. An operation similar to that used in constructing the mineralized models was used to reduce the number of cells by considering the patterns of occurrence among all the variables of interest. The weights derived from the probability matrix for the cells in L1 are listed in Table 3. Classes 1-6 of the degree of match based on these weights are shown in Fig. 3C. All cells in class 5 or class 6 were retained with the exception of one cell outside the model. For this cell, greenstone is present, quartz keratophyre is absent, and anomalous lead was unevaluated so that the relationship in (5) was unevaluated. The cells that comprise the final lithogeochemical model called L2 are shown in Fig. 3D. Comparing Fig. 3D with Fig. 2G reveals that four cells are common to both models and that both models include the two cells containing the Skiftesmyr deposit. After deletion of two variables having negative weights calculated from the product matrix, the set of weights was recalculated; they are listed in Table 3. The classes numbered class 1 to class 8 for the degree of match for the cells in Fig. 2B with the lithogeochemical model L2 are shown in Fig. 3E. All the cells in the model are in class 8 representing the highest degree of match. No other cells in the area are as similar to these, and this relationship suggests that the model is homogeneous and distinct.

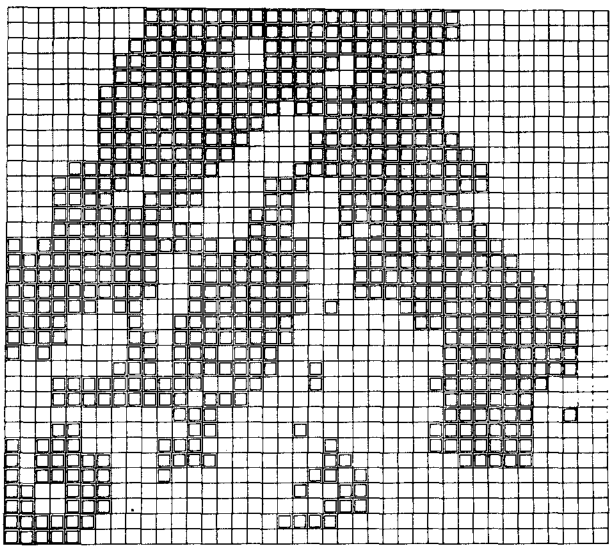
Application of Models in the Gjersvik Area

The Gjersvik area is situated on the northern part of the Grong region (Fig. 1). Within this area, one large deposit and several small deposits have been found (Lutro, 1979). The greenstone units that have been mapped in the area are analogous to those in the area to the south containing the Skiftesmyr deposit, which for reasons stated above was the area selected for constructing the exploration models. The two models, the mineralized M3 and the lithogeochemical L2, were applied in the Gjersvik area. As with the area containing the Skiftesmyr deposit, the cells selected for evaluation were the cells in which either greenstone or quartz keratophyre were present and the cells excluded in which the underlying tuffaceous-sedimentary sequence were present (Fig. 4A). The cells selected for evaluation are shown in Fig. 4B. The results obtained by applying the two models and using the same thresholds within each model for constructing the classes from the degree of match of a cell with each model are shown in Fig. 4C and Fig. 4E for the mineralized and the lithogeochemical models, respectively. The cells in the highest class and surrounding cells in the next highest class for the two models are shown in Fig. 4D and Fig. 4F. These maps show that two areas are favorable for follow-up exploration.

After identifying these areas, the Grong Mining Company decided that the follow-up should be conducted according to normal procedures, namely, detailed geologic mapping, VLF measurements, magnetometry, apex measurements, and collection of stream sediments. In the northernmost favorable area,

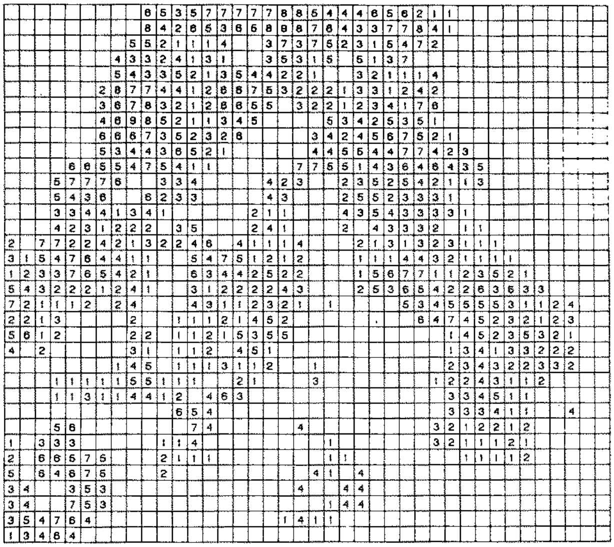


(A)

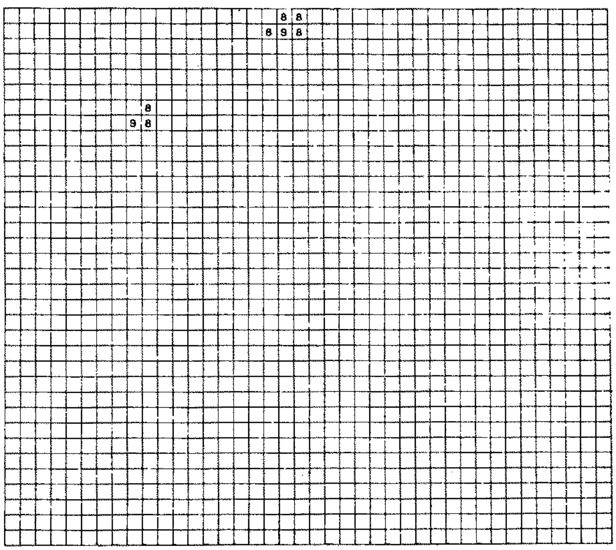


(B)

Fig. 4. Plan maps of the Gjersvik area illustrating the application of the mineralized model M3 and the lithogeochemical model L2. Each cell measures 500 m on a side. (A) Plan map showing areal distribution of an unfavorable tuffaceous-sedimentary sequence. The markings in the cells have the same meaning as the markings in Fig. 2A. (B) Plan map of the outlined cells for which the tuffaceous-sedimentary sequence is absent. These cells contain

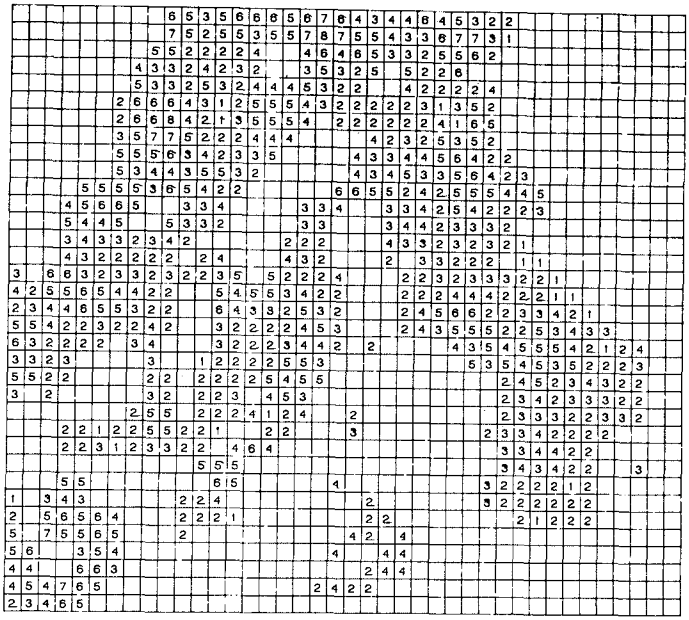


(C)

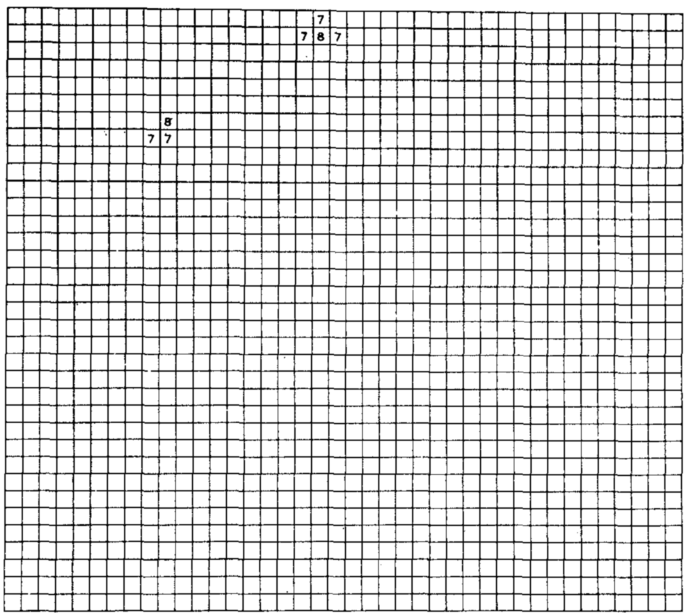


(D)

greenstone, keratophyre, or both. This figure is analogous to Fig. 2B. (C) Plan map of the degree of match of cells outlined in B with mineralized model M3. The cell values correspond to degrees of match, which are the same as those shown in Fig. 2H. (D) Plan map of the cells in C having values of 8 or 9. (E) Plan map of the degrees of match of the cells outlined in B with lithogeochemical model L2. The cell values correspond to degrees of match,



(E)



(F)

which are the same as those shown in Fig. 3E. (F) Plan map of the cells in E having values greater than 7 and associated cells having values equal to 7.

a sulfide vein system was found (Olesen, 1980). It was interpreted as the "feeder-zone" or "root zone" of a potential massive sulfide deposit. Detailed geological mapping further indicated that the volcanic-stratigraphic sequence was partially inverted so that the massive ore, if it does exists, is at a greater depth than the "feeder-zone." In order to test this idea, the Grong Mining Company has scheduled drilling to commence in 1982.

In the other favorable area, promising features were noted; however, intensive postglacial weathering was judged to be responsible for most of the observed geochemical anomalies, and further detailed examination of the volcanic-stratigraphic sequence resulted in the conclusion that the locality was unfavorable.

CONCLUSION

Characteristic analysis allows the combination and use of exploration data to characterize a mineral-deposit model and to determine the degree of match between a given area and a particular model. A model may be based on a mineralized area or may include data on the surrounding area; it can be a nonexisting hypothetical model defined by a geologist. If used by experienced interpreters, characteristic analysis is a valuable tool for (1) target selection in exploration, (2) delineation of favorable areas in regional mineral resource appraisal, and (3) evaluation and appraisal of mineral resources.

APPENDIX

Probability of k or More Matches in n Outcomes of Paired Sequences of +1's, 0's, and −1's

Let s_1^n and s_2^n each represent ordered sequences of n values of +1's, 0's, and −1's. Let p_1, q_1 and p_2, q_2 be the number of +1's and −1's in s_1^n and s_2^n, respectively. Then the number of 0's in s_1^n and s_2^n is $(n - p_1 - q_1)$ and $(n - p_2 - q_2)$ unless $p_1 + q_1 \geqslant n$ or $p_2 + q_2 \geqslant n$, in which case, the number of 0's is zero for the particular sequence.

A match is said to occur at the ith position of the two sequences if $s_{1i}^n = s_{2i}^n = 1$ or $s_{1i}^n = s_{2i}^n = -1$. Let m represent the number of matches that occur for the n positions in the sequences. Then

$$m \leqslant \{\min(p_1, p_2) + \min(q_1, q_2)\}$$

Suppose now we assume that the p_2 values of +1 and the q_2 values of −1 in s_2^n are arranged in a random order and we ask what is the probability that the number of matches m between s_1^n and s_2^n equals r? This probability is given by

$$\Pr\{m=r\}$$

$$=\frac{\sum_{\nu=0}^{r}\binom{p_1}{\nu}\binom{q_1}{r-\nu}\sum_{\alpha=0}^{p_2-\nu}\binom{n-p_1-q_1}{\alpha}\binom{q_1-r-\nu}{p_2-\nu-\alpha}\sum_{\beta}^{q_2-r+\nu}\binom{n-p_1-q_1-\alpha}{\beta}\binom{p_1-\nu}{p_2-r+\nu-\beta}}{n!/p_2!q_2!n-p_2-q_2!}$$

We are interested, however, in calculating $\Pr\{m \geqslant k\}$. We can calculate this by noting

$$\Pr\{m \geqslant k\} = \sum_{r=1}^{k-1} \Pr\{m=r\}$$

which gives us the desired probability.

For large values of n involving many pairs of sequences, s_i^n, s_j^n, the computation of the probabilities is both time consuming and costly, even on a large computer. Therefore, the use of an approximation to the above expression can greatly reduce time and cost. For large n, the probability of m equals r matches is approximated by

$$\Pr\{m=r\} \cong \binom{n}{r}\left(\frac{p_1p_2+q_1q_2}{n^2}\right)^r\left(1-\frac{p_1p_2+q_1q_2}{n^2}\right)^{n-r}$$

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