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Discriminant Analysis as a Method of Predicting Mineral Occurrence Potentials in Central Norway[1]

Alfredo E. Prelat[2]

ıe statistical technique of discriminant analysis is used to define target areas for detailed ˈneral exploration given only general geological information and aeromagnetic anomaly lues. In the test area, located in Central Norway, on-going exploration surveys have revealed ? presence of mineralization; however, it still has not been determined if any of the sites will economically feasible. The area was divided into 1400 1-km × 1-km cells by superimposing square grid on 1:50,000-scale geological and geophysical maps. Later the area was divided ˈo two subareas based on major differences in each area's geology. A number of geological ıtures and the aeromagnetic anomaly values were coded systematically in each cell. The lls representing an advanced degree of exploration were chosen as control cells in each of e subareas. The geological and geophysical parameters were transformed, by means of latively simple transformations, to produce near-normal frequency distributions. A discrimiınt function was then obtained by discriminant analysis to divide the control data into two oups, cells with presence of mineral occurrence and cells without mineral occurrence. ıe discriminant function obtained for the control area proved to be relevant both geologically d statistically. Consequently, the discriminant equation was applied to cells outside the ntrol area. The cells were assigned to one of the two groups by entering the geologic factors ɛasured from the maps into the discriminant model. The exploration potential of a large ımber of cells was evaluated by this procedure. To test the results, field work including ochemical sampling was carried out in the cells with highest probability of mineral occurrnce. The field work results have shown that the application of discriminant analysis to ological information at 1:50,000 scale with 1-km × 1-km cells combined with a careful lection of techniques for transforming the variables is a feasible method for predicting ˈneralization, and as such could become a valuable tool for mining exploration. KEY ORDS: discriminant functions, geochemical exploration, map cells.

INTRODUCTION

ıe present research is part of a project undertaken by the Geological Survey Norway to develop methods for quantitative appraisal of metallic mineral sources. The project covers a study of the existing and potential strata-

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Geological Survey of Norway, N-7001 Trondheim, Norway.

bound, polymetallic, massive sulfide ores of the Caledonian-fold mountaii belt within an area of about 20,000 km^2 in Central Norway. An area locate‹ in the Meråker, Færen, and Flornes mapsheets in the eastern Trondhein region was arbitrarily selected to evaluate the application of discriminan analysis in estimating mineral potential.

This paper describes an application of the statistical technique known a discriminant analysis to the problem of selecting target areas for detaile‹ mineral exploration. Specifically, discriminant analysis was used to classif 1-km × 1-km geographic cells into two groups which are defined by either th presence or the absence of ore mineralization. The statistical discriminatior however, is from 1:50,000-scale geological and geophysical maps. In recer years, multivariate statistical techniques have been applied to assist in minerε exploration by constructing exploration decision models to predict favorabl areas for valuable mineral deposits. Some of these models consider areas o thousands of square kilometers, which in turn are subdivided into cells b superposition of an arbitrary grid. Harris (1965), for example, employed grid in which each cell was equal to 20 square miles (32 km^2). A multivariat relationship was established in a well-known control area and then the minerε potential was estimated in the rest of the cells designated as target area: Agterberg and others (1972), on the other hand, subdivided an area i Ontario and Quebec into cells 10 km × 10 km and selected a number of cell within the region to be used as control cells which were not necessarily adjacen to each other.

In this project, as in Agterberg's work, a number of cells were selected t‹ be control cells, with the difference that instead of being 10 km × 10 km th individual cell size was reduced to 1 km × 1 km. Next, geological and geo physical parameters were measured from maps at scale 1:50,000. The reasoı for selecting 1-km × 1-km cells was because earlier results demonstrated tha prediction of mineral potential is much more effective with this approach Thus, 1-km × 1-km cells on maps at the scale of 1:50,000 are more effectiv‹ than 2-km × 2-km cells on maps at the scale of 1:100,000. The geology in th‹ study area is a complex part of the Norwegian Caledonides, and the geologica variables selected for the statistical model are best demarcated in the 1-km × 1-km cells at scale 1:50,000.

This study made use of geological and geophysical maps from th‹ Meråker, Færen, and Flornes areas situated in the eastern Trondheim regioı (Fig. 1). The test area, which lies on the Central Norwegian Caledonides, i still in an exploration stage. Mineral occurrence has been revealed at severa locations within the study area; however, it still has not been determined i any of these sites will be of economic interest. Sources of information for th‹ study were Geological Survey of Norway publications (Wolff and others 1967, 1974) and unpublished geological maps provided by F. Wolff.

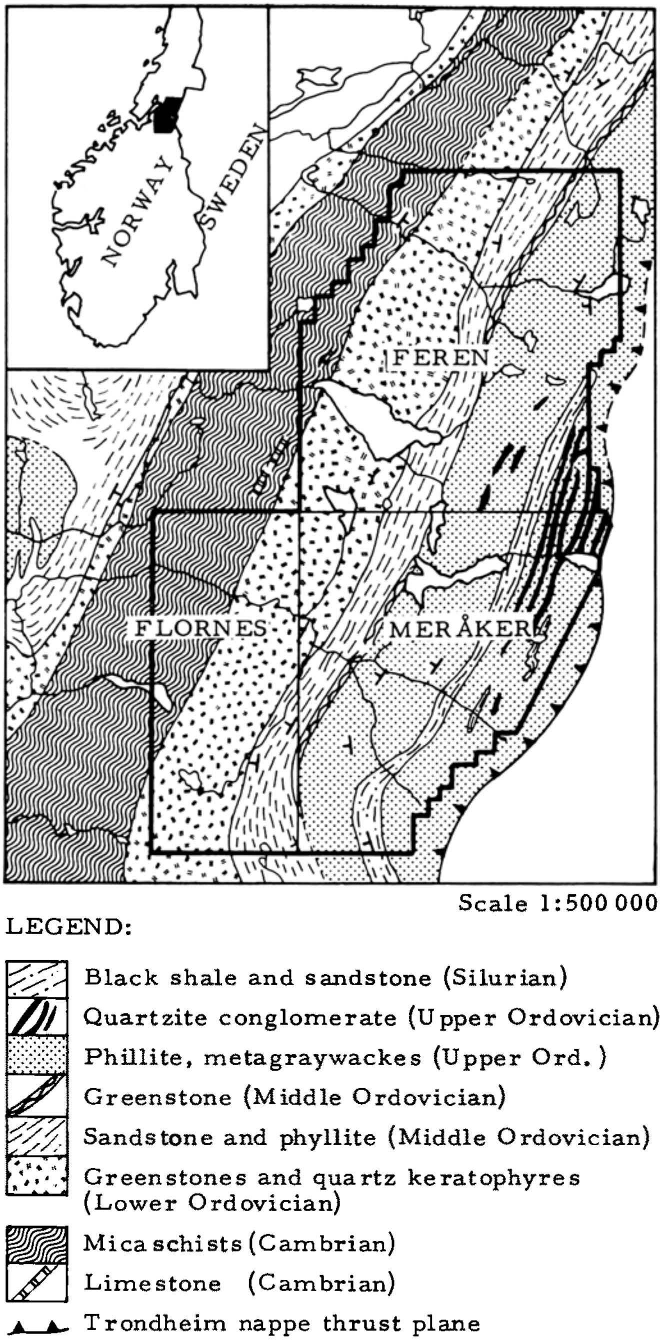


Figure 1. Location of study area and geological map at scale 1:500,000 (from Wolff and others, 1967). Divisions of the mapsheets covered by the study are also indicated.

DESCRIPTION OF THE PROCEDURE EMPLOYED

The first step in the analysis consisted of assembling geological and geophysi cal data for all the geographic cells in the study area by making measurement from geological maps. These data were subsequently organized to be pro cessed by computer.

Statistical analyses such as histograms, coefficients of kurtosis and skew ness, and the χ^2 test were used to study the distribution of the geologica and geophysical variables. As a consequence, three statistical transformation were performed to bring the distribution of the analyzed variables closer t normal distribution. This is necessary in order to apply a statistical test o significance in discriminant analysis, where a basic assumption is that th parent populations are multivariate normally distributed, with the corre sponding variances and covariances equal. The transformations used were th square root of $X+K$, the logarithm of $X+K$, and the arcsine of X as a percent$+K$, where X is the measurement actually taken from the maps, an K is a real constant. The variables which were redundant or did not have an relationship to mineral occurrence were eliminated from the study through a analysis of the correlation coefficient matrix.

The information processed was used as input data for the discriminan analysis model. A discriminant equation was established for a set of contro cells based on the geological and geophysical variables measured. The contro cells were divided into two groups: cells with mineralization present, an cells in which mineralization was absent. Next the discriminant function wa calculated.

At this point, cells from the rest of the area were classified in one of th two groups by entering the geological and geophysical variables measure from the maps to the discriminant equation. The results of the classificatio were used to produce mineral prediction maps by contouring the probabilit values that the cells belong to the mineralized groups.

To test the predictions, an area was arbitrarily selected from which geo chemical stream sediments and soil samples were taken and analyzed Analysis of the stream sediments and soil samples gave results which demon strated the potential of the method as a tool for selecting areas for detaile mineral exploration.

GEOLOGIC SETTING

The study area is located in the Central Norwegian Caledonides and cover about 1400 km^2 of the Meråker, Færen, and Flornes mapsheets. The strati graphy, petrography, and structure of the Central Norwegian Caledonide have been described by Wolff and others (1967) and is well known. A detaile scription of the geology in the Meråker and Færen mapsheets published by olff and others (1974) provided the basic data for this study. The eastern rt of the Flornes mapsheet was included in the study because it has been eviously explored in mining. The geological map for Flornes (unpublished) is also provided by F. Wolff.

The following is a short description of the lithologic column taken from olff and others (1974). The base of the column consists of a tectonic group probable Eocambrian age. It is represented by schistose and gneissose artzofeldspathic sediments and amphibolites of the Steinfjell Group. verlying this, above a major thrust plane, is the metasedimentary and volnic sequence of the Trondheim nappe. The sequence starts with the Sonvass roup of Cambrian age. This group has the highest grade metamorphic ocks in the area and consists of schists and migmatitic gneisses. Veins and eets of acid composition intrude these lithologies. The sequence continues ith the Funnsjø Group of Lower Ordovician age. This group starts with the udå conglomerate which is overlain with a thick igneous complex of metaasaltic quartz-ketatophyre intrusives, and shallow intrusions of metadiorites, etaporphyrites, and meta-albite-granites. The Sulåmo Group of Middle rdovician age continues with a metasedimentary sequence. Overlying the ulåmo Group is the Kjølhaugen Group of Upper Ordovician age with rey-green phyllites, phyllitic greywackes, and greywackes. The sequence nds with the Silurian Slågån Group represented by calcareous metasiltstones r fine grained metasandstones. In the study area Caledonian intrusives are epresented by metagabbros, metadiorites, albite granite, and quartz-rich onalite.

The massive sulfide ore bodies of the Norwegian Caledonides show vidence of two distinct types of sulfide deposits (Vokes, 1962). These include oncordant massive pyritic deposits where the ore bodies as a whole are rgely concordant with the layering or schistosity of their country rocks, nd sulfide deposits with chalcopyrite–pyrrhotite as primary ores, containing ifferent sized fragments of the surrounding country rocks. The ore bodies ccur as flat, irregular plates concordant with the layering of the metamorphic chists that form the country rocks. A detailed description of these two types f sulfide ore bodies is given by Vokes (1962).

Mines and smaller occurrences of ore are disseminated throughout the rondheim region and in several places have been established as mining istricts since the middle of the 17th century. Occurrences of ore minerals of ossible economic importance are of two types (Wolff and others, 1967). he first consists of pyrite occurrences which are frequent within the igneous ocks of the Funnsjø Group (Lower Ordovician) and in basic extrusives in the ektarhaug Formation (Middle Ordovician). The other type consists of alcopyrite occurrences within the greywackes of the Kjerringfjell Formation

(Upper Ordovician) near intrusive sheets of hornblende-metagabbro. At the present time, exploration and assessment surveys are being carried out on several occurrences in the study area. Some of the ore deposits have been mined in the past, but none is being worked at present.

DATA ACQUISITION AND STATISTICAL ANALYSIS PROCEDURE FOR THE VARIABLES

The Universal Transverse Mercator (UTM) grid system was used to subdivide the area into cells of equal dimensions. The UTM grid lines were printed at 1-km intervals on maps at 1:50,000 scale forming a cellular grid system of cells 1 km × 1 km in size. The geology was quantified at each cell by measuring the percentage of rock types, the contact relationships, the distance to major faults from the center of the cell, and the aeromagnetic values at the cell center.

The geological and geophysical variables quantified in order to perform the discriminant analysis were selected for the following reasons:

(1) The geological variables grouped and consistently mapped over the whole area were selected according to the type of rock and its age.

(2) The contact relationship was measured to define possible geologic interactions in contact zones in relation to ore formation. Results showed that the contact relationship was one of the main factors in differentiating cells with ore mineralization from those which are barren.

(3) The regional aeromagnetic anomaly was chosen as a potentially useful indicator of lithologic units in which mineralization occurs. In addition aeromagnetic maps provided valuable information concerning geologic structure useful in exploration.

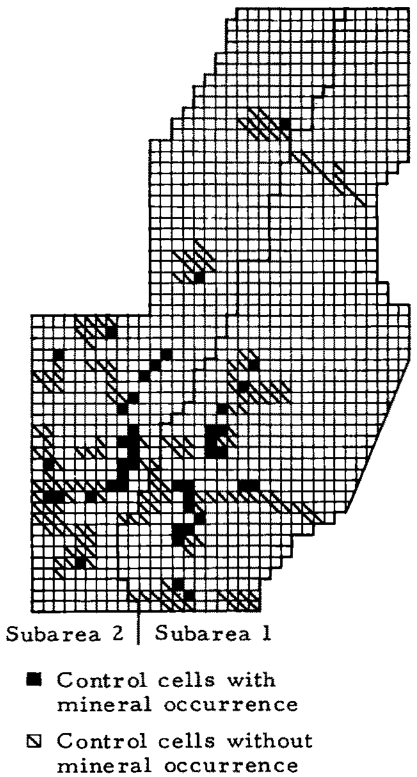
(4) The distance from the center of the cell to major fracture zones is a factor of possible importance in exploring for mineral deposits.

Each of the 1-km^2 cells (2 cm × 2 cm in the 1:50,000 map) was subdivided into 400 (1 mm × 1 mm) subcells. The rock type present in the center of the subcells was registered and then the resulting 400 "presence/absence" type data in each 1-km × 1-km cell were transformed to percentages. For example, if in a given cell 300 subcells were covered by hornblende-metagabbro and 100 subcells by metagreywacke the corresponding percentages are 75 percent hornblende-metagabbro, 25 percent metagreywacke, and 0 percent for the rest of the geologic rock type variables not present in the cell. The total length of the contact among rock types was measured in km, and converted into a number of subcells (1 km = 2 cm = 20 subcells) in order to apply the square-root transformation so that their frequency distribution more nearly approximates a normal distribution. The number of exposures of rock types was counted in each cell. The aeromagnetic anomaly values in gammas were

:orded at the cell center. In the eastern part of the Meråker and Færen ıpsheets (subarea 1), the distance from the center of the cell to the nearest ajor fracture was measured in km and converted into a number of subcells km = 2 cm = 20 subcells) to apply the square root transformation. The ographic cells whose area is covered more than 25 percent by water or by 'erburden were eliminated in the statistical analysis. The aggregate percenges of all rock types in cells covered 25 percent or less by water or overbur- :n were recalculated to 100 percent.

Selection of Subareas and Control Cells

he study area was subdivided into two subareas. The cellular grid super- nposed on the two subareas is shown in Figure 2. Subarea 1 is located in the ıstern part of the study area in the Meråker and Færen mapsheets and con- ıins 719 cells (in addition to 51 cells covered more than 25% by water or verburden). Subarea 2 includes 576 cells (in addition to 54 cells covered



igure 2. Cellular grid superimposed on ıe two subareas. Black cells (mineral :currence) and crossed cells (without ineral occurrence) were used as control ımples to establish the discriminant ınction in each subarea.

more than 25% by water or overburden) and is situated in the western part o the study area in the Meråker, Færen, and Flornes mapsheets. The two mai reasons for dividing the study area into subareas were: (1) most of the roc types present in subarea 1 were absent in subarea 2, including the intrusiv sheets of hornblende gabbro to which mineral occurrence is related in subare 1, and (2) mineral occurrence in subarea 2 is common within the acid igneou rocks and basic intrusives which are not present in subarea 1.

In each subarea a group of control cells was chosen to establish th discriminant equation based on the selected geological variables. Figure shows the control cells in each subarea. Although the control cells were no necessarly adjacent to each other, they were located in well-known areas Some of these areas are currently being actively explored.

Statistical Analysis of Raw Variables

One of the assumptions in the application of the discriminant model is tha the input variables are normally distributed, with all corresponding variance and covariances equal. Moderate departures from normality and from homo geneous covariance, however, may not be serious. A previous analysis of th variables in the control cells was undertaken to find out the form of the distri butions. The analysis involved estimation of means, variances, and coeffi cients of skewness and kurtosis, and employed the chi-square goodness-of-fi test. The results showed that the measured variables were markedly differen from a normal distribution. Consequently transformations were performe to bring the data closer to normality. The behavior of the variables was the examined to avoid introducing errors in the transformation process, allowing an interpretation of the results from the transformed observations in a manner compatible with the original variables.

A number of transformations were tested on each one of the variables according to the form of the original frequency distribution. This involved calculating the distribution before and after transformation, and then selection of a transformation that brought the data closest to normality. The transformations used included:

(1) *Arcsine transformation* (angular transformation). This transformation was used for percentage of rock types. The effect is to stretch out both tails of the distribution of percentages while compressing the middle. This transformation also prevents the variance from being a function of the mean as occurs in a binomial distribution. When the percentages are transformed to angles, the distribution closely approximates the normal. To avoid zero values a constant was added to all the rock type variables coded.

(2) *Square-root transformation*. This was used on the contact relationships, number of exposures, and the distance to major fractures. These data follow

t ɜ Poisson rather than the normal distribution, where the variance is the ꞩ me as the mean. The square-root transformation makes the variance i ɿependent of the mean. Different constants were added to the variables ι ıtil the distribution closest to normality was found.

(3) *Logarithmic transformation*. This was used on aeromagnetic values easured at the center of each cell. The frequency distribution of the original romagnetic values is skewed to the right and is made more symmetrical by e transformation. The transformation involves taking the logarithm of the iginal observation. Different constants were added to the logarithmic ılues until a distribution was found that is close to the normal distribution.

Reduction in Number of Variables

rior to the use of discriminant analysis, the relationships of the geological nd geophysical variables were examined in the correlation matrix. The Pear- ɔn correlation coefficient matrix was calculated between all pairs of variables ı each subarea, both before and after transformation, to make sure drastic ıanges did not occur as a result of the transformation process. The variables ıat were redundant or had no relationship to mineral occurrence were iminated. If two variables had a correlation coefficient greater than 0.90 nd their relationship to the rest of the variables was within a close range ±0.05), one variable was eliminated as being redundant. On the other hand, hen a given variable showed no variation in the correlation matrix with ɜspect to the variables related to mineralization, it was discarded. Of the ariables, 24 out of 36 could be eliminated from the discriminant analysis in ıbarea 2, and 14 out of 23 could be eliminated in subarea 1. The eliminated ariables accounted for very little of the total variance.

Tables 1 and 2 show all the variables in subareas 1 and 2 respectively. he variables selected from the correlation matrix for input to the discriminant ıodel are indicated by an asterisk (*) before the variable number. Initially all ıe variables were used to compute the discriminant functions, but in a ɜcond run, the discriminant function was calculated by using only the ariables selected from the correlation matrix. The results showed an increase ı the statistical significance of the distance between group means when the ss useful variables were dropped. The discriminant function based on the ɜlected variables also proved to be more efficient by showing the highest ercentage of correct sample assignments into the two groups.

DISCRIMINANT ANALYSIS PROCEDURE

he main objective in applying discriminant analysis to large geologic areas as to select those cells most favorable for detailed mineral exploration.

Table 1. Variables in Subarea 1. Variables Marked with Asterisk (*) Were Selected from Correlation Matrix to Compute Discriminant Function

Age and type of rock

*1. Percent of cell area consisting of Caledonian intrusive hornblende-metagabbro (Teveldal)
2. Percent of cell area consisting of Lower Ordovician greenstone and amphibolite (Fundsjø Group)
3. Percent of cell area consisting of Middle Ordovician limestone, grey phyllite, and metagreywacke (Sulåmo Group)
*4. Percent of cell area consisting of Middle Ordovician grey calcareous metasandstone (Sulåmo Group)
*5. Percent of cell area consisting of Middle Ordovician greenstone and greenschist (Sulåmo Group)
6. Percent of cell area consisting of Middle Ordovician grey sericite phyllite (Sulåmo Group)
7. Percent of cell area consisting of Upper Ordovician grey sericite phyllite (Kjølhaug Group)
*8. Percent of cell area consisting of Upper Ordovician grey-green metagreywacke (Kjølhaug Group)
9. Percent of cell area consisting of Upper Ordovician metaconglomerate (Kjølhaug Group)
10. Percent of cell area consisting of Upper Ordovician grey-green slate and phyllite (Kjølhaug Group)
*11. Percent of cell area consisting of Silurian grey metasandstone, grey slate, and grey phyllite (Slågån Group)

Contact relationships

*12. Length of the contact of Caledonian intrusive hornblende-metagabbro (Teveldal) with Upper Ordovician grey-green metagreywacke (Kjølhaug Group)
*13. Number of exposures of the contact in variable 12
14. Length of the contact of Caledonian intrusive hornblende-metagabbro (Teveldal) with Upper Ordovician grey-green slate and phyllite (Kjølhaug Group)
15. Number of exposures of the contact in variable 14
16. Length of the contact of Middle Ordovician greenstone and greenschist (Sulåmo Group) with Middle Ordovician grey-calcareous metasandstone (Sulåmo Group)
17. Number of exposures of the contact in variable 16
18. Length of the contact of Middle Ordovician greenstone and greenschist (Sulåmo Group) with Upper Ordovician grey sericite phyllite (Sulåmo Group)
19. Number of exposures of the contact in variable 18
20. Length of the contact of Middle Ordovician greenstone and greenschist (Sulåmo Group) with Upper Ordovician grey-green metagreywacke (Kjølhaug Group)
21. Number of exposures of the contact in variable 20

Structural relationships

*22. Distance from cell center to thrust plane

Regional aeromagnetic anomaly

23. Aeromagnetic values measured at the center of each cell

ble 2. Variables in Subarea 2. Asterisk (*) Indicates Variables Selected to Compute Discriminant Function

e and type of rock

- * Percent of cell area consisting of Caledonian intrusive hornblende-metagabbro (Hermanssnasa)
- Percent of cell area consisting of Caledonian intrusive fine- to medium-grained metadiorite (foliated)
- Percent of cell area consisting of Caledonian intrusive fine- to medium-grained metadiorite (massive)
- Percent of cell area consisting of Caledonian intrusive fine- to medium-grained metadiorite
- Percent of cell area consisting of Caledonian intrusive albite-granite (gneissified)
- Percent of cell area consisting of Caledonian intrusive quartz-rich tonalite (Trondhjemite)
- Percent of cell area consisting of Cambrian migmatite gneiss (Sonvatn Group)
- Percent of cell area consisting of Lower Ordovician greenstone and quartz-keratophyre (Fundsjø Group)
- Percent of cell area consisting of Lower Ordovician quartz-ketatophyre (Fundsjø Group)

0. Percent of cell area consisting of Lower Ordovician porphyritic greenstone and greenstone amphibolite (Fundsjø Group)
1. Percent of cell area consisting of Middle Ordovician dark grey to black phyllite (Sulåmo Group)

ntact relationships

2. Length of the contact of Caledonian intrusive hornblende-metagabbro (Hermanssnasa) with Caledonian intrusive fine- to medium-grained metadiorite
3. Number of exposures of the contact in variable 12
4. Length of the contact of Caledonian intrusive hornblende-metagabbro (Hermanssnasa) with Cambrian migmatite gneiss (Sonvatn Group)
5. Number of exposures of the contact in variable 14
6. Length of the contact of Caledonian intrusive fine- to medium-grained metadiorite with Caledonian intrusive albite-granite (gneissified)
7. Number of exposures of the contact in variable 16
8. Length of the contact of Caledonian intrusive fine- to medium-grained metadiorite with Cambrian migmatite gneiss (Sonvatn Group)
9. Number of exposures of the contact in variable 18
0. Length of the contact of Caledonian intrusive fine- to medium-grained metadiorite with Lower Ordovician quartz-keratophyre (Fundsjø Group)
1. Number of exposures of the contact in variable 20
2. Length of the contact of Caledonian intrusive fine- to medium-grained metadiorite with Lower Ordovician porphyritic greenstone and greenstone amphibolite (Fundsjø Group)
3. Number of exposures of the contact in variable 22
4. Length of the contact of Caledonian intrusive fine- to medium-grained metadiorite with Middle Ordovician dark grey to black phyllite (Sulåmo Group)
5. Number of exposures of the contact in variable 24
6. Length of the contact of Caledonian intrusive albite-granite (gneissified) with Cambrian migmatite gneiss (Sonvatn Group)

Table 2. Continued

27. Number of exposures of the contact in variable 26
*28. Length of the contact of Caledonian intrusive albite-granite (gneissified) with Lower Ordovician porphyritic greenstone and greenstone amphibolite (Fundsjø Group)
*29. Number of exposures of the contact in variable 28
30. Length of the contact of Caledonian intrusive quartz-rich tonalite (Trondhjemite) with Cambrian migmatite gneiss (Sonvatn Group)
31. Number of exposures of the contact in variable 30
32. Length of the contact of Lower Ordovician quartz-ketatophyre with Cambrian migmatite gneiss (Sonvatn Group)
33. Number of exposures of the contact in variable 32
34. Length of the contact of Lower Ordovician quartz-ketatophyre with Lower Ordovician porphyritic greenstone and greenstone amphibolite (Fundsjø Group)
35. Number of exposures of the contact in variable 34

Regional aeromagnetic anomaly
36. Aeromagnetic values measured at the center of each cell

Since mineral occurrence is in part presumed to be a result of the geologic process reflected in the regional geology, the discriminant model was used as a tool to relate the probability of mineral occurrence to the regional geology.

A simple example will illustrate the use of discriminant analysis in our study (for mathematical background, see Davis, 1973). Suppose we select a set of control cells that can be separated into two groups based on the presence or absence of ore mineralization. The classification of the cells is determined by the application of a discriminant function of the form:

$$Z = A_0 + A_1 X_1 + \dots + A_n X_n$$

where Z is the discriminant score; $A_0, A_1, \dots, A_n$ are discriminant coefficients; and $X_1, \dots, X_n$ are the discriminant variables defined as percentage of different rock types, contact relationships, distance to major fractures, and aeromagnetic values measured from the geological and geophysical maps.

A critical value of Z (discriminant index) is calculated for the control set which defines the limit on the discriminant function line between the two groups. A Z value (discriminant score) is calculated for each cell by entering the measured variables in the cell into the discriminant function. If the discriminant score of the geographic cell is above the discriminant index the cell is classified in one group; if it is below the discriminant index, it is classified in the other group (the discriminant index is half-way between the means of the discriminant scores for the presence and absence of mineral occurrence groups). Given a cell which is not part of the control set used to obtain the discriminant function, the group to which the cell most probably belongs can be established by simply calculating its discriminant score.

The probability that a cell belongs to one of the two groups can be lculated and varies directly as the squared distance between the cell and the ean of the group that is being considered. This distance is represented by the ometric distance between sample and group means. For each sample to be ssified, the probability of belonging to each of the two groups is computed, e largest indicating the most probable group. The probabilities of the cells longing to the mineralized group were mapped over the study area.

Discriminant analysis also examines the significance of each geological operty in the process of discriminating between groups. Some geologic riables are more reliable indicators of mineralization than others. For example, the percent in each cell of Lower Ordovician greenstone proved to be e most important geologic property in discriminating between the two oups in subarea 2. Consequently, discriminant analysis was used to evaluate e significance of each variable as a means of classifying the cells in one of e two groups. The discriminant technique applied in the present work is own as stepwise discriminant analysis. By the stepwise method, the discriminant function is not obtained by considering all the variables as a whole, it rather the variables are used independently and consecutively in order of eir discriminatory power in classifying the cells into groups. The computer ogram used is the BMD07M stepwise discriminant analysis program, part the BIOMED package (Dixon, 1970).

CRITERIA EMPLOYED TO SELECT THE CELL SIZE ACCORDING TO THE MAP SCALE

ap scale was the criterion employed to select the size of the cells. The choice size was decided upon as a result of the following test:

) A grid with cells 2 km × 2 km was superimposed on 1:100,000-scale ological maps. Each of the 2-km × 2-km cells (2 cm × 2 cm in 1:100,000 aps) was subdivided into 400 (1 mm × 1 mm) subcells and the geological riables were coded systematically in each subcell.

) The geological variables were measured again in the 1:100,000 maps using 1-km × 1-km cells (1 cm × 1 cm in the 1:100,000 maps) each cell ing subdivided into 100 subcells (1 mm × 1 mm).

The geological variables were measured again, this time using the 1:50,000 ps with cells 1 km × 1 km (2 cm × 2 cm in the 1:50,000 maps) subdivided o 400 subcells (1 mm × 1 mm). Due to the greater detail at a scale of 1:50,000, vas necessary to divide the geological factors used with the 1:100,000 maps o more categories. For example, areas that were mapped as granitic rocks ledonian intrusive) at the scale of 1:100,000 can be broken down into the re specific categories of albite-granite and quartz-rich tonalite at the scale 1:50,000.

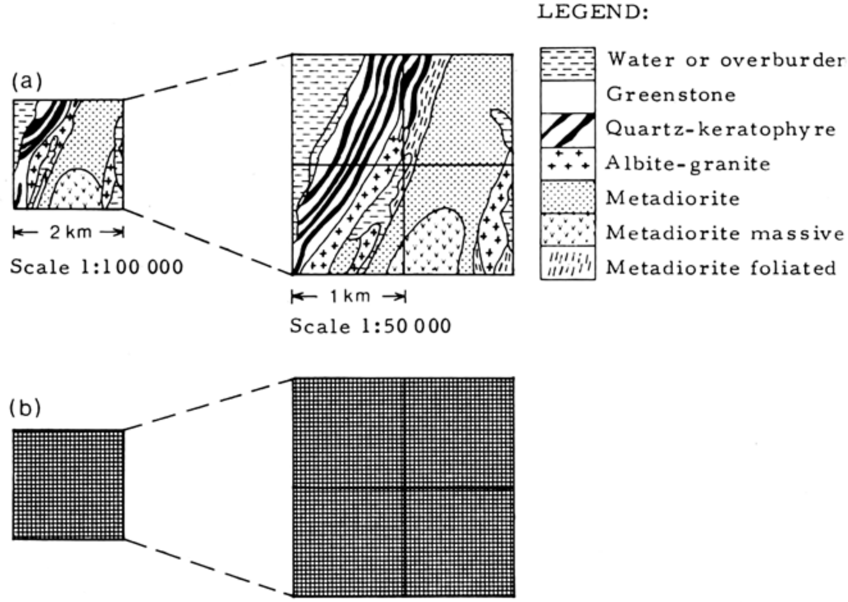


Figure 3. Increase in number of subcells in the same area as a result of using different scales: (a) the 2-km × 2-km cell at 1:100,000 scale was divided into four 1-km × 1-km cells on the 1:50,000 map due to more detailed information; (b) division of grid squares increasing the number of subcells from 400 to 1600 used to code the geology in part (a).

(4) Once the measurements with the three cell sizes were completed, the data were transformed and the discriminant function computed. Variables that were redundant or had no relationship to mineral occurrence were eliminated. (5) The discriminant analysis technique was applied to the three sets of data obtained with the different cell sizes.

As a result of these experiments, it was concluded that the distributions of the geological variables measured at the scale of 1:50,000 in 1-km × 1-km cells were better defined than at a scale of 1:100,000 because of the increase in the number of subcells from 400 to 1600 (Fig. 3). The use of 1:50,000 maps facilitated selection of constants used in transforming the variables.

It was also concluded that the discriminant function could not be computed by using the information within 1-km × 1-km cells superimposed on the 1:100,000 maps. This cell size was not adequate to differentiate between cells with mineralization and cells without mineralization at the scale of 1:100,000.

The discriminant function calculated by using the information quantified in the 1-km × 1-km cells at the scale of 1:50,000 was more effective as a

Table 3. Comparison for the Same Area of BMD07M Outputs Obtained with Information Quantified in Control Cells with Mineralization Using Maps at Different Scale. (A) Shows Classification Results Using Information at Scale of 1:50,000 with 1-km × 1-km Cells. (B) Shows Results Using Information at Scale of 1:100,000 with 2-km × 2-km Cells

Group MINE, case	Group with largest probability	Square of distance from and posterior probability for group			
		MINE		NONE	
(A)					
1	MINE	18.512	0.981	26.452	0.019
2	MINE	12.333	0.572	12.912	0.428
3	MINE	13.033	0.691	14.645	0.309
4	MINE	13.512	0.740	15.607	0.260
5	MINE	24.065	0.924	29.054	0.076
6	NONE	9.274	0.157	5.914	0.843
7	MINE	9.782	0.870	13.576	0.130
8	MINE	14.497	0.999	28.490	0.001
9	MINE	5.777	0.954	11.831	0.046
10	MINE	11.879	0.743	13.999	0.257
11	MINE	18.379	0.995	28.786	0.005
12	MINE	18.199	0.995	28.916	0.005
13	MINE	6.537	0.987	15.179	0.013
14	MINE	45.195	1.000	65.173	0.000
15	MINE	17.805	0.864	21.508	0.136
16	MINE	15.386	0.958	21.619	0.042
17	MINE	19.862	0.987	28.514	0.013
18	MINE	37.608	1.000	63.355	0.000
19	MINE	8.105	0.893	12.358	0.107
(B)					
1	NONE	59.112	0.487	59.010	0.513
2	NONE	18.865	0.232	16.473	0.768
3	MINE	7.931	0.993	17.793	0.007
4	MINE	21.215	0.987	29.920	0.013
5	MINE	7.219	0.973	14.420	0.027
6	NONE	17.105	0.049	11.193	0.951
7	MINE	28.221	0.641	29.383	0.359
8	NONE	8.284	0.290	6.489	0.710
9	NONE	9.208	0.118	5.193	0.882
10	NONE	32.994	0.169	29.804	0.831
11	MINE	6.870	0.639	8.011	0.361
12	MINE	8.406	0.997	20.068	0.003
13	MINE	8.406	0.997	20.068	0.003
14	MINE	179.269	1.000	200.554	0.000
15	MINE	8.869	0.999	23.021	0.001
16	MINE	9.311	0.999	24.293	0.001
17	MINE	11.646	1.000	28.012	0.000
18	MINE	179.271	1.000	200.550	0.000

classifier, and therefore the results were better than when using the information from the 2-km × 2-km cells at the scale of 1:100,000. This demonstrated that the cells 1 km × 1 km superimposed on the 1:50,000 maps were the adequate size to register the variation in the geology and to define the targets in the study area. Furthermore, the control cells were very well defined as separate groups with the geological information contained in the 1-km × 1-km cells at scale of 1:50,000, which served to establish reliable discriminant functions to later define the "exploration potential." It is important to point out that the discriminant functions were also computed before transforming the data. In all cases better results were obtained after transformations of the variables.

Table 3 compares the outputs from the BMD07M program for these control samples with mineral occurrence (group MINE) which served as a test group for the same area using information from maps at scale 1:50,000 with 1-km × 1-km cells (Table 3A) and maps at scale 1:100,000 with 2-km × 2-km cells (Table 3B). The number of cases in each table are not the same due to the different scale and cell size used to measure the geological variables. The result for the classification of the control cells without mineral occurrence (group NONE) is not shown in the table. Each line in the table represents a sample with a case number, the group with the largest assignment probability, the squared distance between the sample and the mean of the group, and the probability of belonging to the group MINE (cells with mineral occurrence) or NONE (cells without mineral occurrence). For example, in Table 3A the first sample was classified as MINE because the probability which varies directly with the squared distance was greater for MINE (0.981) than for NONE (0.019).

Inspection of Table 3A shows that all the samples were properly classified with the exception of one case, in comparison with Table 3B where six samples were misclassified. The misclassified 2-km × 2-km cells were located in areas where the geology was more representative for the control group NONE. Geographic cells with a large squared distance, as for example Case 14 in Table 3B, represent geological conditions which were similar to, but not representative of, the control groups. These problems reflect the fact that a map scale of 1:100,000 made it difficult to identify the geology associated with mineral occurrence because of the coarser demarcation of lithologic units and contact relationships. Even though the misclassified cells and the cells with large squared distance in Table 3B were removed from the control group, the classification of cells outside the control areas using information from the 1:100,000-scale maps was not consistent and yielded unreliable results. The following section discusses the prediction of mineral occurrence based on information from the maps at a scale of 1:50,000.

PREDICTION OF EXPLORATION POTENTIAL

ıe main purpose of this study has been to predict the presence or absence mineralization in cells outside the control areas in terms of geological and ophysical variables. A group of cells from each subarea was chosen to tablish the discriminant equations based on the geological and geophysical ıriables presented in Tables 1 and 2. These control areas are in an advanced age of exploration and include most of the known mineral occurrences. hey are also representative of the geology of the overall area. The discrimi-ınt functions were established in each one of the subareas, each cell being presented by transformed geological variables. The stepwise discriminant ocedure was used to calculate the discriminant function between the cells ith mineral occurrence and the cells without mineral occurrence of the con-ol data set. These functions, which proved to be statistically and geologi-ılly reliable, were used to classify the cells outside the control areas into ne of the two groups. The assignment of the unidentified cells to one of the vo groups was accomplished by entering the selected transformed variables ıeasured from the map into the discriminant model.

Results in Subarea 1

he control cells in subarea 1 include most of the known mineral occurrences ·lated to near-by intrusive sheets of hornblende gabbro and consist of 100 ells out of 719 cells. Table 4 gives results for the 619 cells outside the control reas which were classified in one of the two groups. The table indicates that 6 or 13.89 percent of the unclassified cells were assigned to the group with resence of mineralization, and 533 or 86.11 percent to the group with ab-nce of mineralization.

The significance of each geological variable in statistically discriminating tween the two groups was also established in subarea 1. Table 5 lists the

Table 4. Number of Control Samples in Subarea 1, and Number of Unclassified Cells Assigned to Control Groups

Type of sample	Group	Number of cases
control	MINE	20
	NONE	80
samples classified outside control areas	MINE	86
	NONE	533

Table 5. Order of Selection, According to Discriminatory Power, of Geological Variables in Subarea 1 by Stepwise Discriminant Analysis

1. Percent of cell area consisting of Middle Ordovician greenstone and greenschist (Sulåm Group).
2. Length of the contact of Caledonian intrusive hornblende-metagabbro (Teveldal) with Upper Ordovician grey-green metagreywacke (Kjølhaug Group).
3. Percent of cell consisting of Upper Ordovician grey-green metagreywacke (Kjølhaug Group).
4. Number of exposures of the contact hornblende-metagabbro with grey-green metagreywacke.

main geological variables according to their effectiveness in separating the two groups. The most important variable listed in Table 5 is the percent of cell consisting of Middle Ordovician greenstone and greenschist (Sulåm Group) reflecting the fact that the percent of greenstone and greenschist is very high in cells with mineral occurrence. The second variable is the length of contact between the Caledonian hornblende-metagabbro (Teveldal) and the Upper Ordovician grey-green metagreywacke of the Kjølhaugen Group. This contact often coincides with mineralized cells. The next significant variable is the percentage of cells containing grey-green metagreywacke of the Upper Ordovician Kjølhaugen Group, which is usually present in mineralized cells. Following is the number of exposures of the contact hornblende metagabbro with grey-green metagreywacke.

Results in Subarea 2

Subarea 2 contains 108 control cells in a total of 576 cells. Mineralization occurs in the Lower Ordovician igneous rocks and in basic extrusives of the Middle Ordovician age. Table 6 shows the results of classifying cells outside

Table 6. Number of Control Samples in Subarea 2, and Number of Unclassified Cells Assigned to Control Groups

Type of sample	Group	Number of cases
control	MINE	23
	NONE	85
samples classified	MINE	42
outside control areas	NONE	426

ıble 7. Geological Variables in Subarea 2 Listed in Decreasing Order of Discriminatory Power

	Percent of cell area consisting of Lower Ordovician porphyritic greenstone and greenstone amphibolite (Fundsjø Group).
	Length of contact of Caledonian intrusive albite-granite with Lower Ordovician porphyritic greenstone and greenstone amphibolite (Fundsjø Group).
	Length of contact of Caledonian intrusive hornblende-metagabbro (Hermanssnasa) with Caledonian fine to medium metadiorite.
	Number of exposures of the contact hornblende-metagabbro with fine to medium metadiorite.

ıe control cells. A total of 426 cells (91.0%) were predicted to have no ıineral potential, but 42 (9.0%) are classified as having strong potential in ‹ploration. The geologic variables selected as having discriminatory power ı separating the groups in subarea 2 are listed in Table 7. The first variable the percent of cells consisting of porphyritic greenstone and greenstone mphibolite in the Lower Ordovician Fundsjø Group. Mineralization is enerally associated with this rock type. The second variable is the length of ontact between Caledonian intrusive albite-granite, and Lower Ordovician orphyritic greenstone and greenstone amphibolite. This contact measured ı km was usually present in mineralized cells. Other variables include the ontact relationship between the Caledonian hornblende-metagabbro (Herıanssnasa) and the intrusive Caledonian metadiorite, and the number of xposures of the contact hornblende-metagabbro with fine to medium metaiorite.

Interpretation of Mineral Occurrence Prediction Maps

o facilitate interpretation of results, a probability estimate that a geographic :ll belongs to the mineral occurrence group (MINE) was assigned to the :nter of each cell in the study area and contoured. The contour maps inude both cells belonging to control groups as well as cells outside the ›ntrol areas. Two values are attached to each geographic cell, one being the ·obability that the cell belongs to the mineralized group and the other that e cell belongs to the baıren group. The sum of the probabilities is equal to 0, reflecting the fact that one of the outcomes must occur if the cell is pros:cted. Figures 4, 5, and 6 show the maps for the probability of correct signment for the three mapsheets in the study area. The contour maps were oduced by the SYMAP graphic display system and later redrawn by hand.

Flornes mapsheet. The probability contour map for this area (Fig. 4) esents an interesting set of "exploration potentials" for further detailed

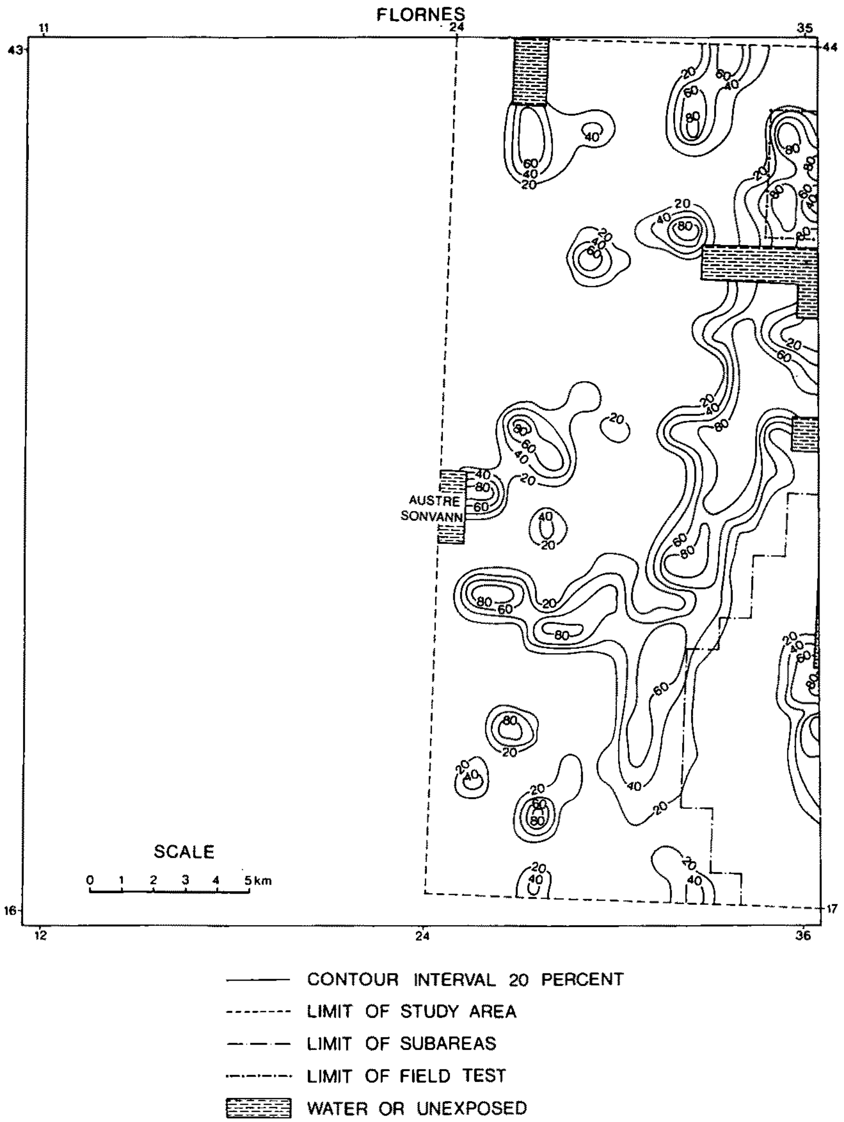
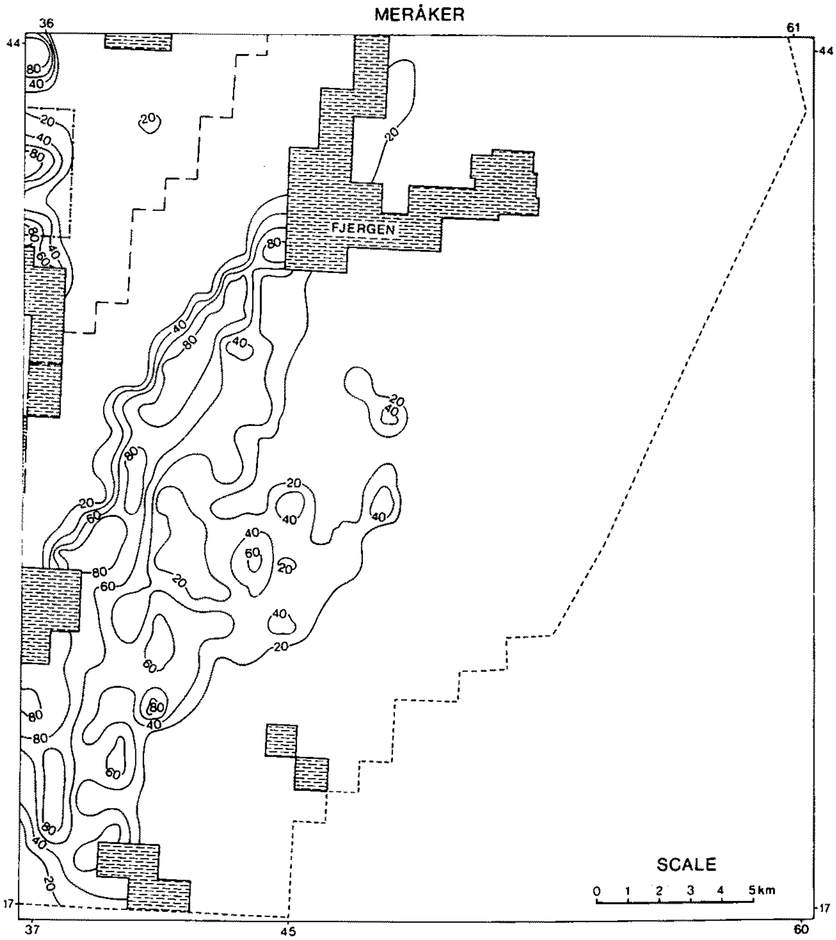


Figure 4. Map showing probability of correct assignment to the mineralized group in the Flornes mapsheet area.



——— CONTOUR INTERVAL 20 PERCENT

-------- LIMIT OF STUDY AREA

— — — LIMIT OF SUBAREAS

-·-·-·- LIMIT OF FIELD TEST

WATER OR UNEXPOSED

Figure 5. Map showing probability of correct assignment to the mineralized group in the Meråker mapsheet area.

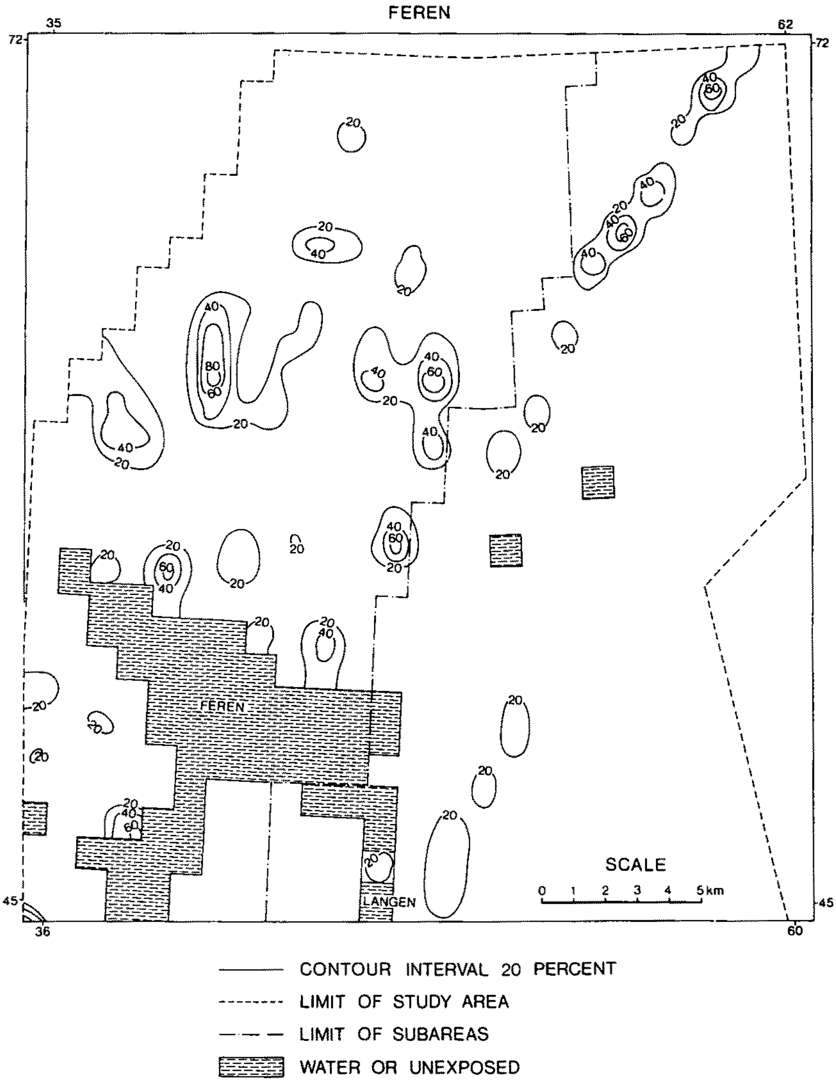


Figure 6. Map showing probability of correct assignment to the mineralized group in the Færen mapsheet area.

prospecting. The areas predicted to be favorable for exploration are generally aligned in a NE–SW trend. Promising areas are usually related to the presence of Lower Ordovician greenstone amphibolite, and to places where the quartz-keratophyre and greenstone amphibolite occur in contact. The northeastern part of the map area was selected for subsequent field work to test the forecasting results.

Meråker mapsheet. Promising areas are represented by the high proba- lity assignment values in Figure 5; they follow a NE–SW trend. The central- est and southwestern parts of the area are suggested as favorable for further xploration. The exploration potential in the southwestern part coincides ith cells where Caledonian metagabbro (Teveldal) is in contact with Upper rdovician grey-green metagreywacke. The eastern part of the area appears nfavorable.

Færen mapsheet. The forecast exploration potential is shown in Figure 6, here promising areas are generally correlated with the presence of Middle rdovician greenschist and hornblende-metagabbro.

FIELD TEST

n exploration geochemical survey to test the predictions was conducted in n area of about 20 km^2 located in the northeastern part of the Flornes map- heet quadrangle and the northwestern part of the Meråker mapsheet quad- angle. Stream sediments and soil samples were analyzed for 11 elements. igure 7 is a contour map representing the zinc content in the samples. The

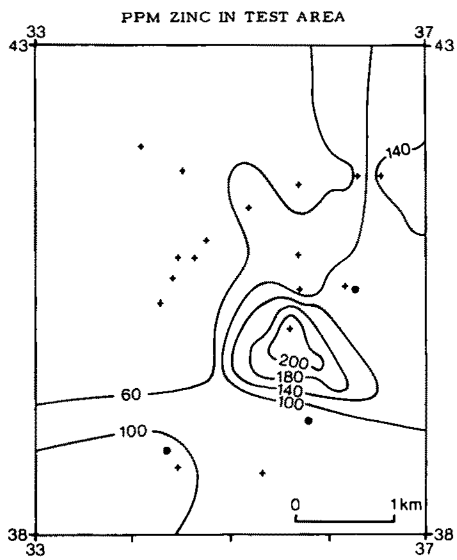


Figure 7. Contour map for zinc data. The contour values are given in parts per million, and the locations of samples are indicated by crosses. Small degrees of mineral occurrence are indicated by solid circles.

geographic cells containing the mineral occurrence are part of the contro l group for subarea 2.

Inspection of the contour map shows two areas with high zinc conten The high in the south-central part of the map, which lies along the contac albite-granite and greenstone, is greater (over 200 ppm) than the high in th northeastern part (over 140 ppm), which lies along the contact of quartz-ric tonalite and greenstone. Both highs are located in geographic cells whic were classified in the mineralized group (see Figs. 4 and 5). Similar result were obtained for copper and lead. Further geochemical sampling at close intervals between sample points and geophysical methods such as induce polarization and resistivity surveys will be required to better define th anomalies.

CONCLUSIONS

Discriminant functions can classify favorable areas for subsequent detaile exploration in a more objective and consistent manner than conventiona procedures. Cell size in tabulating geological variables must be selecte according to the scale of the map and type of target. In this case study, discriminant functions calculated using information in 1-km × 1-km cells at a 1:50,000 scale proved more effective than 2-km × 2-km cells on maps o 1:100,000 scale.

Cells 1 km × 1 km superimposed on 1:50,000 maps were adequate to register geological variation that identifies targets (mineralized cells) in the Trondheim region. At a scale of 1:100,000, with 2-km × 2-km cells, however, many cells in the control groups were misclassified or presented a large squared distance in "discriminant space" reflecting the fact that at this scale the relationships between the geology and mineral occurrence are poorly defined. When using 2-km × 2-km cells, the classification of cells outside the control areas was inconsistent.

One of the problems in this study was to select the geological variables that are most effective in computing the discriminnt functions. In the two subareas, the geological variables were selected according to their relationship to mineral occurrence, and those that were redundant were eliminated. Statistical transformations were necessary to bring the geological variables closer to normal distribution. The shapes of the original distributions of the geological variables were well-defined at a 1:50,000 scale, facilitating the selection of constants in the transforming equations.

Geological maps, aeromagnetic surveys, and the presence of ore mineralization were the only information used in this study. If regional geochemical surveys (such as the one conducted in the test area), specific gravity surveys, and production and reserve statistics from mining districts were available in ldition to the geological and aeromagnetic data, the ability to predict exploration potential" should be improved.

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