Trace elements in magnetites as pathfinders for base-metal deposits in Dalecarlia, Sweden

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Magnetite is present in various amounts in all known rock types in the area investigated; it is always present in the till derived from these rocks. The trace element assemblages in magnetite differ, however, considerably between, and to some extent within, the different rock types, so it should be possible to predict the provenance of magnetites taken from till. By analysing the content of Ti, V, Co, Ni, Mn, Zn, and Cu in magnetites from both bedrock and till samples, and then using fuzzy-set theory for clustering of the rock samples, it was possible to get likelihood-estimates of the contribution of each rock type to each till sample. Furthermore, the magnetites from skarns associated with sulphide ores are fortunately very distinct from other magnetites, so very small proportions of magnetite related to sulphide-ore can be accurately detected in the till samples.

All known sulphide-ore mineral occurrences in the area gave rise to anomalies some 1—5 "downstream" in the general direction of the ice flow. Several anomalies were found which could not be related to known mineral occurrences, of which at least one is related to a newly discovered mineral deposit. It has also been possible to mathematically estimate the degree of dilution of magnetites related to different rock types in the till, and hence increase the amount of information from each till sample considerably.

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Introduction

Glacial till has long been used for base-metal prospecting and originally only the coarsest parts of the till were used, i.e. boulder tracing. More recently, however, the finer fractions have also been utilized permitting sampling. Problems arise, however, in quantitatively relating the till to its bedrock source as different minerals are selectively weathered both mechanically and chemically, which may lead to a severely distorted picture of the source rocks when, for instance, the heavy minerals of till are evaluated. Furthermore this makes it very difficult, if not sometimes impossible, to estimate distance of transport for the finer fractions of the till. The transport distances are of interest not only for Quaternary geologists but also for prospectors, e.g. when ore-minerals which survive glacial transport are found in the till. An attractive method therefore would be to analyse the trace element content of some reasonably resistant and abundant mineral, which is present in all rock types and all till samples in the area under study. The mineral in question should also possess characteristic trace element assemblages for the different rock types.

In the early sixties Theobald & Thompson (1962) and Theobald et al. (1976) in the United States demonstrated that the trace elements in magnetites taken from stream sediments varied considerably. This feature was credited to variations in trace element content of magnetites from different types of source rock. In the present study it quickly became evident that the trace element composition of magnetite could be used as a reliable indicator of the provenance and transport distance of till if a way of distinguishing the magnetites from different source rocks was found. From Table 1, which shows arithmetic and geometric means and standard deviations for different trace elements in different rock types, it is apparent that there are compositional differences in the magnetites from the different rock types in the study area. Developments in multivariate statistics and pattern recognition have proceeded very rapidly during the last decade, and by taking advantage of some of the more recent mathematical and statistical methods avai-

Table 1. Statistical parameters for distribution of Ti, V, Co, Ni, Mn, Zn, and Cu in magnetites in the study area.

		Ti %	V ppm	Co ppm	Ni ppm	Mn ppm	Zn ppm	Cu ppm	n_i
Older granites	$\bar{x}$	0,17	392	144	436	3470	182	862	13
	G	0,11	329	105	250	2880	149	427	
	SD	0,17	222	104	378	1860	125	1180	
Metavolcanics and metasediments	$\bar{x}$	0,31	950	458	1580	4990	766	744	18
	G	0,20	588	193	654	3270	340	494	
	SD	0,28	1080	835	3040	6950	1060	688	
Younger migmatites and gneisses	$\bar{x}$	0,35	954	175	494	2530	448	589	18
	G	0,23	636	118	256	2070	271	332	
	SD	0,35	1008	143	470	1400	466	497	
Younger coarsely porphyritic granites	$\bar{x}$	1,46	428	143	472	3700	335	561	11
	G	0,39	310	104	266	2930	253	359	
	SD	2,34	314	124	396	2180	251	465	
Younger fine-grained ..	$\bar{x}$	0,24	653	156	422	2190	182	346	19
	G	0,15	473	91	212	1570	138	181	
	SD	0,27	461	149	430	1820	163	350	
Diorite and gabbro	$\bar{x}$	0,68	2330	95	683	1120	822	2160	18
	G	0,39	1110	64	227	959	380	287	
	SD	0,65	2280	86	1380	652	1170	5600	
Skarn related to sulphide mineralization	$\bar{x}$	0,06	625	136	902	753	1080	1710	8
	G	0,05	98	61	37	628	266	501	
	SD	0,04	1470	162	2470	598	2360	3170	

$\bar{x}$ = arithmetic mean, G = geometric mean, SD = standard deviation, n_i = initial number of observations in each group.

lable, it has become possible to characterize distinct classes of magnetite from different rock types, and also to sort out from a mixture, the till, the proportions likely to originate from the different rocks.

Study area

The area, of just over 1000 km^2, is situated NNW of Falun (a copper mining town since at least the 11th century AD). The bedrock consists of older and younger Svecofennian granites, younger Svecofennian migmatites and gneisses and, oldest of all, the leptites consisting of metavolcanics and metasediments. There are also several diorites and gabbros in the area, which stratigraphically belong to the older Svecofennian granite group. The numerous occurrences of sulphides in the area are mostly in the leptites (Hjelmqvist 1966). The Quaternary features in the area are generally fairly straight forward (Lundqvist 1951), except for some recent finds of an older fine-grained till (Erikson 1977) with a more westerly origin than the common till, which is present almost universally in the area. The extent of the older till is not known at present but it is suspected that it might underlie a considerable part of the area.

Methods

Samples of bedrock were taken mainly at outcrops marked on the geological map and in addition many new road cuttings were sampled. Furthermore old mining sites were sampled for skarn. Thus the bedrock sampling localities are somewhat unevenly distributed geographically.

The areal distribution of the till samples is more regular due to the dense network of forestry roads, and only some minor areas covered by glaciofluvial sediments and lakes were left unsampled. The till samples were taken in road cuttings where possible, otherwise a pit, about 1 m deep, was dug and sampled at the bottom benath the C-horizon. The size of the till samples was about 0,5—1 kg and that of the rock samples was from 0,5 to 2,5 kg with the larger samples being from rocks with a low content of dark minerals.

The rock samples were crushed and sieved and the fraction from 355—63 μm was retained for further processing. The till samples were washed in acetic acid and hydrogen peroxide and sieved. All samples were then separated in tetrabromoethane and the heavy fraction was finely ground and then repeatedly separated with a hand magnet to obtain as pure a fraction as possible. It was then weighed and dissolved in hydrochloric acid, leaving impurities such as hematite, ilmenite and silicates undissolved. Any pyrrhotite present also dissolved but was revealed by its smell (the only sample with pyrrhotite was discarded). The solution was filtered and analysed by atomic absorption for Ti, V, Co, Ni, Mn, Zn, and Cu. By using this rather mild acid treatment the fresh parts of the magnetites go into solution and martitized parts tend to remain undissolved.

Statistical evaluation

The problem is, as previously stated, to find similarities between the bedrock, a training set, and the till, an unknown set. The training set can be divided into subclasses, either a priori based on knowledge of the rock types or strictly mathematically by some clustering algorithm. A combination of the two can also be used and is used here.

Hitherto most methods for deciding class membership have been so called "hard" methods, i.e., a rock sample had to be a member of one, and only one, class. So expressions like 70 % granite and 30 % gneiss are not permitted. In the last few years, however, an entirely new way of thinking has emerged in pattern recognition, namely that of fuzzy sets or fuzzy logic (Bezdek 1981), which at once allows data sets with observations sharing membership over the classes. This is desirable in this case as the trace elements in magnetite in a certain rock type will fluctuate geographically and also show features of neighbouring rock types. Further it is not only desirable but necessary in the case of the unknown set, the till samples, as they are practically always mixtures of different parent rocks. Although it is desirable to allow the rock samples to share membership over the classes, the classes themselves should be as distinct as possible for the next step, when the till samples are related to the rocks.

The mathematical treatment can be briefly summarized as follows: the rock samples are each assigned to one of the seven major rock types present in the area. This assignment is based purely on the "eyeball technique", i.e., on prior geological and petrological knowledge. Then the mean vectors and covariance matrices were calculated for each class. To begin with, the means were used as prototypes for each class and the Euclidean distance was calculated from each rock sample to each class mean. The results were very poor indeed, as most rock samples became members of most classes simultaneously; some improvement was achieved, however, when instead of using just the means as prototypes the first few principal axes were included in the prototype model. These axes are the principal components of the covariance matrices for each group.

One way of evaluating the degree of partition between the classes is by using the partition coefficient

$$F(U; c) = \sum_{k=1}^{n} \sum_{i=1}^{c} (u_{ik})^2/n; \ 0 \leqq u_{ik} \leqq 1$$

for c classes and n samples or observations, where u_{ik} is the degree of membership of sample k in class i. The value for F(U; c) always lies between 1/c, 0,1429 in this case, and 1, where 1/c represents equal membership in each class for each sample and 1 means that every samples is a member of one, and only one, class. As can be seen from Table 2, the result for Euclidean distances to prototypes is not very impressive.

It was initially suspected that the distinction between the different classes was not only dependent on differences in the means, but also on dispersion or covariances. By using only the variances and covariances as parameters for the distances, in this case generalized distances, and putting the class means at the grand mean following Beauchamp et al. (1980), the partition coefficient improves considerably (Table 2). A

Table 2. Partition coefficients, F(U; c), for different methods used to distinguish rock types.

Method	F(U; c)
a. Partitions derived from differences in group means, Euclidean distances	0,2921
b. Partitions derived from differences in covariance matrices, no difference in means assumed	0,5560
c. Partitions derived from differences in means as well as covariances	0,6752
d. Same as c. but with weighted memberships, two iterations	0,7279

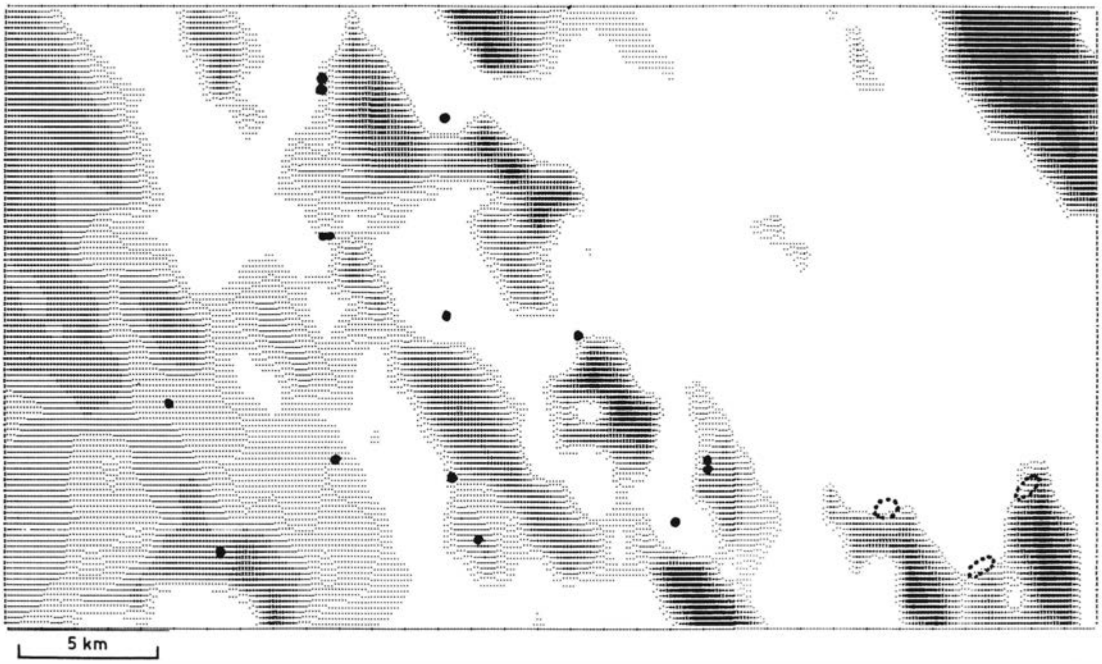

Fig. 1. Map of magnetite in till related to sulphide skarns. The intensities shown are logarithmically scaled membership values. The darkest areas represent values over 0,4 and blank areas values under 0,05. The map is based on a 1 km square grid which has been created by point kriging. Sulphide ore deposits are marked by ● and the enclosed areas are regions with several small mineralisations.

combination of the above two methods showed as expected a still better value for F(U; c), as shown for method c.

The calculation of the generalized distance from each rock sample to the prototype of each class can be summarized thus:

$$\hat{\gamma}_{ik} = \langle x_k - \bar{x}_i, x_k - \bar{x}_i \rangle_A - \alpha \sum_{j=1}^{q} \langle x_k - \bar{x}_i, d_{ij} \rangle_A^2 \; ; \forall i, k,$$

where $\hat{\gamma}_{ik}$ is the "squared distance" between an observation x_k and a prototype; d_{ij} is one of q principal axes or components; A is the weighting matrix, in this case the inverse of the covariance matrix for the class under consideration; $\bar{x}_i$ is the vector of means for the same class; and α is a constant chosen between 0 and 1 to decide how much influence the principal axes are to have in the model. The notation $< >$ refers to the inner product (Bezdek 1981; Granath 1983).

The degree of membership might then be calculated in a variety of ways, in this case a bayesian approach was used. The values of u_{ik} can now be used for weighting the rock samples and new values for means and dispersion calculated. This in turn will eventually give new values for u_{ik} and the process can be continued until it converges or at least the training set contains reasonably distinct and stable clusters (Granath 1983).

At this stage the unknown set of till samples is related to the training set and values for membership calculated. In this step it can be advantageous to compare the distances from the samples to a prototype and its complement, i.e. a prototype calculated from all training samples except those belonging to the class under study. This gives better contrasts, especially for classes with low overall membership values in the till, such as the class related to sulphide ores (Granath 1983).

The membership values for a certain class are then plotted on a map. A plotting routine found useful in this case was point kriging based on linear variograms, which vary anisotropically in different directions due to the glacial transport (Burgess & Webster 1980). The result for magnetites related to sulphide skarns, versus all other magnetites combined, can be seen in Fig. 1, which reveals that the known suphide ore deposits do show up more or less markedly and that there are

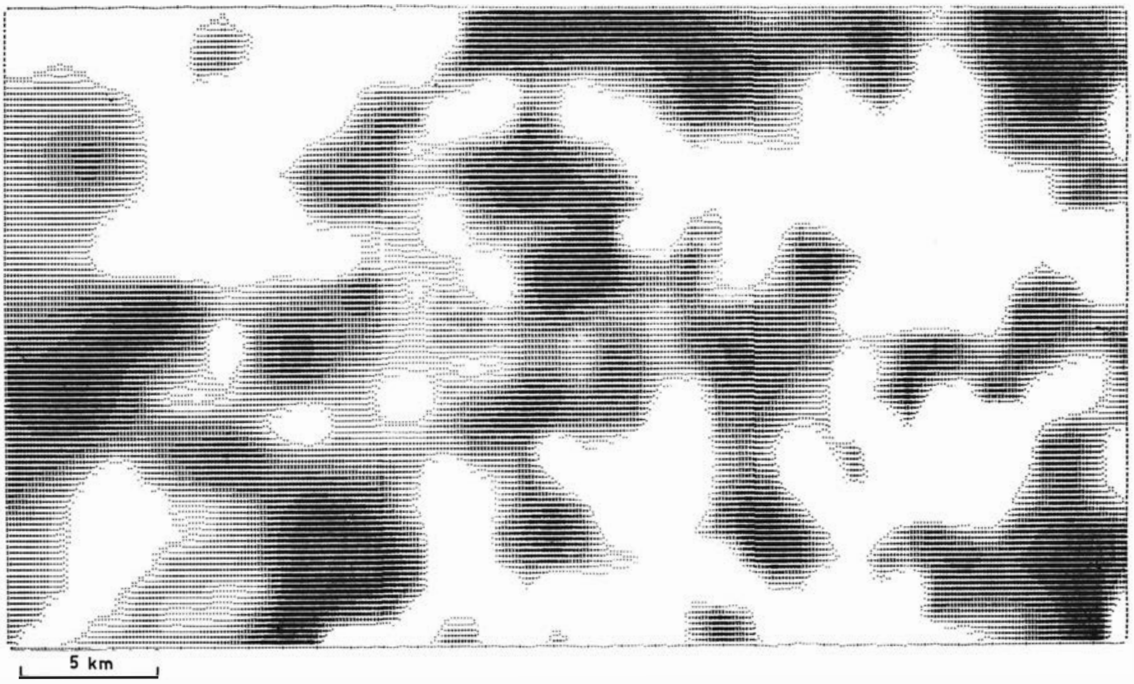

Fig. 2. Map of "short transported" magnetite in till related to sulphide skarns. This map shows to what degree the portion related to skarn also shows covariance properties of skarn. The map is not quantitative in the sense of the map in Fig. 1.

several other areas enriched in magnetite possibly related to suphide ores.

When samples are contrasted between a prototype and its complement it is possible to estimate how much of the background displays properties of the class under consideration or the other way around. This is accomplished by moving the hyperellipsoid representing the class under study so that its origin coincides with that of the complement or vice versa and memberships were calculated for both cases. Two maps concerning skarn related magnetites, derived from such a study are shown in Figs. 2 and 3. The two patterns appear to be displaced in relation to each other in the general direction of the ice movement, and can be interpreted as displaying respectively short and long transported parts of magnetite assemblages related to ore (Granath, in prep). This technique is still very much in its infancy, but the results so far achieved do agree with the known reality too well to be merely a coincidence. In fact, some tests were conducted by constructing cross variograms in several directions over the pair-wise observations. These revealed fairly strong positive cross variances at a lag of 1,0—2,5 km in the general direction of ice movement (330°). Fainter positive cross variances appeared in more westerly directions, about 290—310° at lags of 11,2—14,6 km, which might correspond to an older ice movement whose till may have been partially incorporated into the latest till, which was the one sampled. In other directions no significant positive cross variances were found. This gives a hint not only about the directions of the ice movements, which have long been known in the area, but also about the distances involved, which have been discussed for many decades without a consensus.

Conclusions

The techniques briefly described here might appear somewhat complex but are in fact rather straightforward. The chief features can be summarized as follows. Magnetite is sampled from different rock types and from till and the differences in the trace element content of the magnetites from different rock types are categorized. Then the trace element content of magnetites from tills are examined for similarities with magnetites from different rock types, and values representing

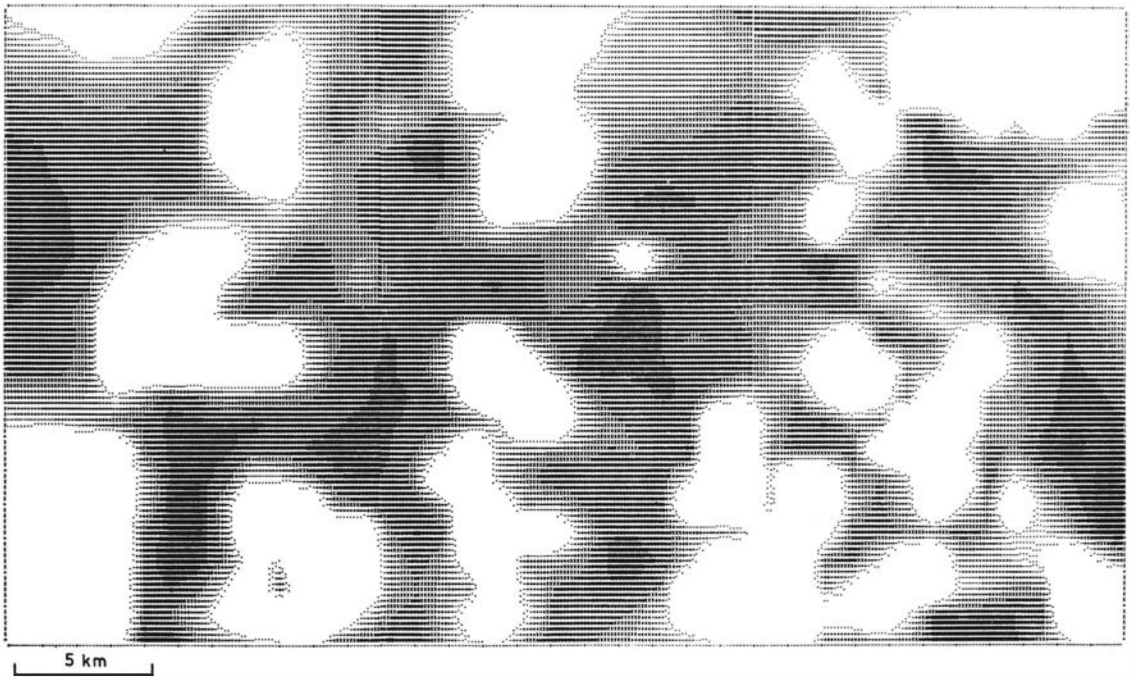

Fig. 3. Map of "long transported" magnetite in till related to sulphide skarns. This map shows to what degree the background displays covariance properties of skarn.

the degrees of correspondence are plotted on maps. By separating quantitative and qualitative similarities it has been possible to get an idea of probable distances of transport, and thus vastly increase the amount of information from the till samples. Magnetite is perhaps the easiest mineral to separate into a monomineralic fraction, and by dissolving this fraction in cold hydochloric acid and analysing by atomic absorption, a reasonably cheap and accurate method has been provided.

The most critical part is to get a representative training set, i.e. an adequate sampling of representative samples from all rock types that might have contributed to the till. A useful objective for the future would be the creation of a database or a library containing large numbers of magnetite analyses, from which data for desired magnetite types could be retrieved and included in the model together with the data from tills, stream sediments or whatever sampling medium is used.

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