Commun. Fac. Sci. Univ. Ank. Series C
V. 6, pp 361-379 (1988)

# AN EXAMPLE TO THE EVALUATION OF GEOCHEMICAL DATA BY MULTIVARIATE GEOSTATISTICAL ANALYSES: DİVRİĞİ REGION IRON DEPOSITS, CENTRAL ANATOLIA

HENRİK STENDAL* and TANER ÜNLÜ**

ABSTRACT

Geostatistical analyses were carried out on 160 rock samples for 24 elements from the Divriği iron ore region. The samples were initially treated as one population. Thereafter the individual rock types were divided into several groups and geostatistically analysed. The geostatistical methods are described shortly for Univariate and Bivariate analyses and, most importantly, the multivariate methods such as Discriminant-, Cluster-, and Factor analyses.

The results of the geostatistical analyses yield a division into different rock groups (Discriminant analysis) and several elementassociation (Cluster-and Factor analyses), which reflect the different rock types. In the individual groups the elementassociation tells more about the geological processes e.g. serpentinization and hydrothermal alteration. The difference between Cluster- and Factor analyses is seen in the Factor analysis, which is a little more differentiated, enabling a more subtle interpretation of the possible geological environment.

The interpretation of the elementassociation suggests that the iron ores are closely associated with mafic to ultramafic rocks, their serpentinization and also later haydrothermal events.

## INTRODUCTION

This paper gives an introductory review of the geostatistical methods, which normally are applied in the treatment of geochemical data with examples from the Divriği iron ore field. All the geochemical data used is published in Ünlü and Stendal (1986). The various methods employed will be shortly described and illustrated as they are the tools in geochemical investigations. Before the description of the multivariate analyses the univariate methods (histogram, cumulative, frequency curve) and bivariate analysis (e. g. correlation coefficients) will be described. The geostatistical analyses have been carried out in the SAS

* Institute of General Geology, University of Copenhagen, Denmark.
** General Directorate of Mineral Research and Exploration (MTA), Ankara, Turkey.

Statistical Analysis System) (Allen 1982, 1985) programme at the Faculty of Science, University of Copenhagen (IBM 4341).

The geology of the Divrigi area will not be described, but only mentioned with references, as it is not the aim here to give a detailed geological introduction. However, results from fieldobservations and microscopic studies will be mentioned in the discussions.

## GEOCHEMICAL STATISTICAL METHODS

For large amounts of geochemical data geostatistical methods may help in the interpretation of this data (Thompson 1983). The first requirement of a geochemical population to obtain reliable results is that the data shows a normal distribution. The histogram shows the distribution, which should be bell shaped. For construction of the histogram using major elements, the analyses are used results directly, but trace elements are normally log–transformed. After the log transformation the data should be normally distributed if sufficient numbers of analyses have been carried out. The second requirement is that the number of samples exceeds 60. Lesser amount of samples might not( ?) be normal distributed. The grafical construction of the histogram is given in Tennant & White (1959), Lepeltier (1969), Boom (1981) and Sinclair (1983). The cumulative frequency curve is constructed from the histogram and from this curve information is given on 1) background, 2) threshold and 3) anomaly values (Lepeltier 1969). The background equalizes with the 50 % value (geometric mean) on the curve and a possible threshold is for a single population–97.5 % of the curve or if the data amount contains two populations, the threshold is defined where the frequency curve is broken. All the values over 97.5 % or over the broken line are anomalies. These definitions are normally used in geochemical exploration.

An example of the grafical construction is given from the Divriği region, where the distribution is shown for Fe, Cr and Ni. The histogram for Fe (Fig. 1–1) yields two populations one with low values from the granitic rocks and host rocks and another population with high values representing the iron ores. These two populations give a broken line in the cumulative frequency curve (Fig. 1–2). This shows a graphical threshold of 72 % $Fe_2O_3$. The Cr distribution (Fig. 1–3, 5) in the histogram with the raw figures (Fig. 1–3) is skewed to the left, toward low values (negative skewness). The log–transformed Cr–data (Fig. 1–4) has three populations. The population with lowest values reflects the granitic rocks. The middle group represents the iron ores and the population with the high values is the serpentinites (host rocks). The cumulative frequency curve is broken twice representing the thresholds between the populations (Fig. 1–5). The Ni distribution shows a similar pattern as (Cr (Fig. 1–7). The high column at the left side of the histogram is due to the analytical detection limit (values below 10 ppm). The cumulative frequency cuive gives a threshold value around 1200 ppm (Fig. 1–8).

The next step in the geostatistical calculation is the correlation coefficients, which are estimated between two elements (McCammon 1974). These coefficients lie between + 1 and –1. Plus one means a perfect correlation between two elements. Minus one means a perfect negative correlation and zero means absolutely no correlation. The correlation coefficient data from the Divriği region is given in Ünlü & Stendal (1986) and these data forms the basis for the multivariate geostatistical analyses in this paper. Here is only given the correlation coefficients between $Fe_2O_3$ and the other elements (Table 1, N= 160). In Table 2 is the correlation coefficients in the granitic rocks (N=15) between $Fe_2O_3$ and Cr, Co given, where the correlation between $Fe_2O_3$ and Cr is 0.50. This relatively high correlation value is only an expression caused of the low variation of the Cr content in granitic rocks. The Co and $Fe_2O_3$ correlation is –0.54 but again the Co variation is low in the granitic rocks.

The multivariate geostatistical analyses give the interrelation between all the samples and all the elements. In the following discriminant analysis, cluster analysis and factor analysis are shortly described, which also can be found in the literature e.g. Kock & Link (1971), Davis (1973) and Howarth & Sinding–Larsen (1983).

*Discriminant analysis*

During statistical treatment of geochemical data the question of reasonable group division always occur, how to divide the collected samples? The problem might be solved with help from the discriminant analysis. Discriminant analysis techniques are aimed at devising an optimum set of rules for the classification of a sample into one of a number of pre–defined groups based on a number of measurements (Howarth & Sinding–Larsen (1983). In other words the discriminant analysis informs us if the sample is correctly or wrongly classified. Grafically it is shown in a X–Y diagram (Fig. 2) where similar samples should group together in the diagram. The individual groups should also be grouped in different places in the diagram, which indicate a difference between the respective groups.

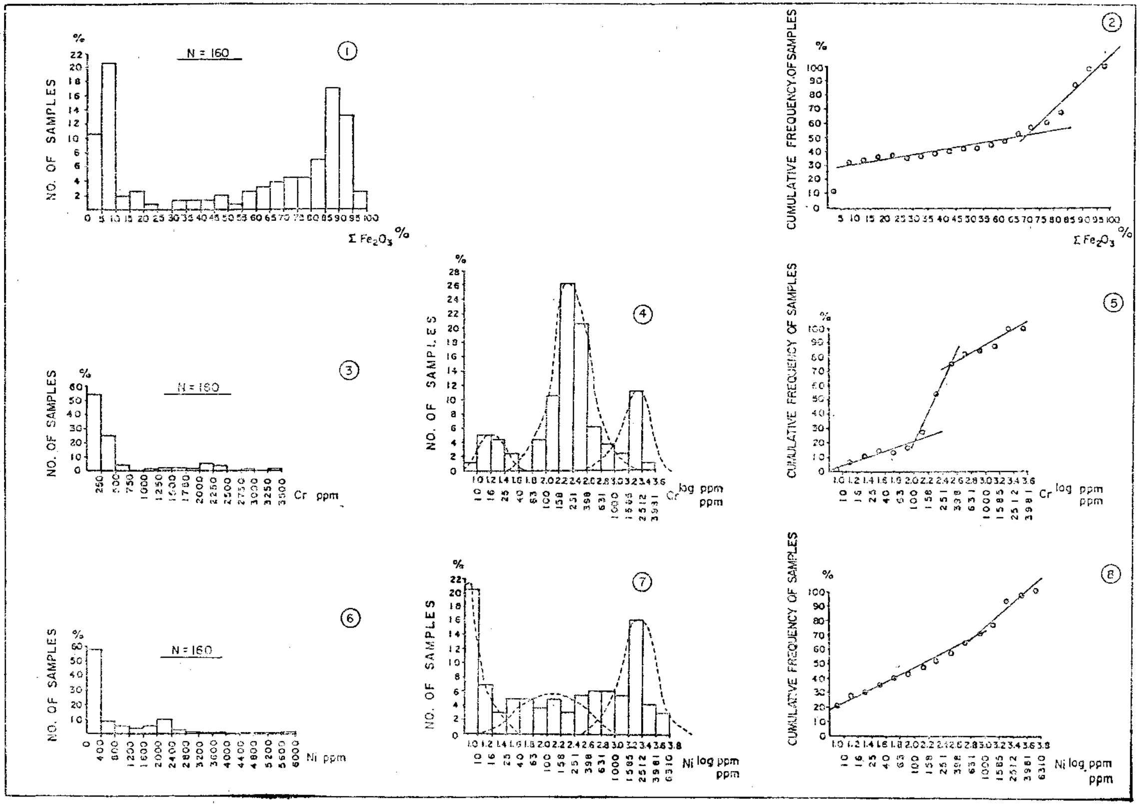


Fig. 1. Histogram and cumulative frequency curve for $Fe_2O_3$, Cr and Ni. Figs. 1–1, 1–3 and 1–6 show the values of the elements. Figs. 1–4 and 1–7 show the log-transformed values for Cr and Ni. Figs. 1–2, 1–5 and 1–8 are the respective cumulative frequency curves (N = 160).

The method used in this paper is a socalled Canonical Discriminant Analysis, which is one of several discriminant methods. The basic calculations for the discriminant analysis are mean and standard deviations of the individual groups. The variation of the individual groups is estimated and the canonical factors given and illustrated e.g. Fig. 2. A general description of discriminant analysis is given in Howarth & Sinding–Larsen (1983) and a more practical example is described in Clausen & Harpoth (1983).

*Cluster analysis*

With cluster analysis it is possible to treat the samples in two ways. The sample information is placed in a matrice, where a m x m matrice (m = sample no.) is called the Q–mode. The calculation of the matrice will cluster the sample together, in principle the way we saw in the discriminant analysis. A m x n matrice –R–mode–is more often applied in cluster calculations, where m again is the number of samples and n is the number of analyzed elements. In the R–mode method the elements are clustered together.

As basis for the calculations the correlation coefficients are used. The two highest correlation coefficients will be clustered together, the procedure continues with calculation of the average of these two coefficients which again cluster together with the nearest similar coefficient and so on. The interpretation of the clustering is visual done with the socalled dendrogram e.g. in Fig. 3. Cluster analysis is in the literature described e.g. Davis (1973), Hesp & Rigby (1973), Obial & James (1973), Levinson (1974), Bell III (1976) and Howart & Sinding–Larsen (1983).

*Factor analysis*

Factor analysis is also a multivariate method for reducing the complexity of a given set of intercorrelated data by accounting for the observed correlations among the variables in terms of the fewest possible number of underlying factors (Levinson 1974). Factor analysis is very extensively described in the literature e.g. Davis (1973) and Howarth & Sinding–Larsen (1983). In a O–mode factor analysis information about the individual sample is given, but this is not used in this paper. Here R–mode factor analysis is used. In the R–mode factor analysis results in obtaining the interrelationship between the individual elements. The following procedure for the R–mode calculation is used: As basis the correlation coefficients are used and the interrelation between these

Table 1. Correlation coefficients between $Fe_2O_3$ and other elements (N = 160).

| | | | | | 1 | 2 |
|---|---|---|---|---|---|---|
| | Granitic Rocks (N = 18) | Serpentinite (N = 5) | "A-Kafa" Host Rock (N = 13) | "B-Kafa" Host Rock (N = 15) | "A-Kafa" Ore (N = 13) | "B-Kafa" Ore (N = 12) |
| $SiO_2$ | —0.78 | —0.55 | —0.46 | —0.97 | —0.97 | —0.60 |
| $TiO_2$ | 0.79 | 0.65 | 0.13 | 0.92 | —0.47 | 0.24 |
| $Al_2O_3$ | —0.46 | 0.63 | 0.22 | —0.06 | —0.96 | 0.06 |
| MnO | 0.92 | 0.99 | 0.04 | 0.04 | —0.03 | 0.41 |
| MgO | 0.79 | —0.81 | —0.18 | —0.97 | —0.91 | 0.43 |
| CaO | 0.66 | 0.17 | 0.10 | 0.18 | —0.33 | —0.60 |
| $Na_2O$ | —0.82 | 0.00 | —0.10 | 0.04 | —0.34 | 0.04 |
| $K_2O$ | —0.72 | 0.38 | 0.14 | 0.75 | —0.89 | —0.03 |
| $P_2O_5$ | 0.79 | 0.71 | —0.17 | —0.55 | —0.33 | —0.11 |
| Cu | —0.29 | —0.56 | —0.42 | 0.10 | 0.10 | 0.21 |
| Zn | 0.56 | 0.96 | 0.40 | 0.73 | 0.35 | —0.24 |
| Pb | —0.41 | —0.01 | —0.46 | —0.52 | —0.01 | —0.32 |
| Ni | 0.74 | —0.80 | 0.10 | —0.75 | —0.02 | 0.18 |
| Co | —0.08 | —0.41 | 0.17 | 0.96 | 0.74 | 0.71 |
| V | 0.88 | —0.23 | 0.54 | 0.82 | 0.13 | 0.37 |
| S | 0.23 | —0.47 | —0.28 | 0.44 | 0.28 | 0.21 |
| Cr | 0.80 | —0.61 | 0.26 | —0.11 | 0.70 | 0.57 |
| Ba | —0.48 | 0.00 | 0.13 | 0.94 | —0.26 | 0.02 |
| Sr | 0.40 | 0.30 | 0.09 | 0.15 | 0.08 | —0.51 |
| Zr | —0.35 | 0.68 | 0.09 | 0.95 | —0.42 | 0.21 |
| Ga | —0.32 | 0.00 | 0.53 | 0.91 | 0.36 | 0.80 |
| Rb | —0.66 | 0.70 | 0.36 | 0.59 | —0.61 | 0.03 |
| Cl | —0.10 | —0.83 | 0.25 | —0.57 | 0.26 | 0.54 |

| 3 | 4 | 5 | 6 | 7 | 8–9 | 10 | |
|---|---|---|---|---|---|---|---|
| Otlukilise (N = 13) | Akdağ (N = 10) | Karahalka (N = 11) | Bizmişen (N = 10) | Kurudere (N = 10) | Sultanmurat and Akuşağı (N = 9) | Attepe (N = 13) | Attepe Host Rock (N = 8) |
| —0.98 | —0.58 | —0.29 | —0.95 | —1.00 | —0.90 | —0.72 | —0.34 |
| —0.97 | —0.09 | 0.16 | —0.84 | —0.99 | —0.63 | —0.71 | —0.64 |
| —0.98 | 0.03 | 0.21 | —0.78 | —0.99 | —0.69 | —0.71 | —0.50 |
| 0.68 | 0.00 | —0.59 | —0.29 | —0.40 | —0.32 | —0.46 | 0.20 |
| —0.56 | 0.67 | 0.38 | —0.82 | —0.87 | —0.17 | —0.59 | —0.27 |
| —0.56 | —0.44 | —0.75 | —0.76 | —0.98 | —0.40 | —0.64 | 0.13 |
| —0.96 | 0.19 | 0.31 | 0.02 | —0.71 | 0.07 | —0.85 | —0.54 |
| —0.97 | —0.15 | 0.07 | —0.24 | —0.52 | —0.74 | —0.71 | —0.39 |
| —0.38 | —0.14 | 0.16 | —0.31 | —0.78 | 0.48 | —0.39 | —0.34 |
| —0.76 | 0.00 | —0.34 | —0.08 | —0.26 | 0.29 | —0.41 | 0.89 |
| 0.83 | 0.37 | —0.53 | 0.52 | 0.75 | 0.16 | —0.64 | 0.05 |
| —0.94 | —0.03 | —0.72 | 0.36 | —0.50 | 0.00 | —0.54 | 0.15 |
| —0.95 | 0.30 | —0.74 | —0.25 | —0.65 | 0.43 | —0.71 | 0.93 |
| 0.97 | 0.61 | 0.89 | 0.49 | 0.56 | 0.80 | 0.97 | 0.69 |
| —0.60 | 0.32 | 0.02 | 0.29 | —0.38 | —0.08 | —0.12 | —0.49 |
| —0.88 | —0.15 | —0.11 | —0.28 | —0.54 | —0.46 | —0.01 | 0.88 |
| 0.98 | 0.71 | 0.76 | 0.62 | 0.91 | 0.84 | 0.97 | —0.40 |
| —0.44 | 0.30 | —0.05 | 0.32 | 0.80 | —0.12 | —0.34 | —0.23 |
| —0.67 | 0.05 | —0.27 | —0.27 | —0.80 | —0.31 | —0.29 | —0.12 |
| —0.94 | 0.50 | 0.26 | —0.78 | —0.05 | —0.55 | —0.54 | —0.51 |
| 0.54 | 0.48 | 0.64 | 0.81 | 0.96 | 0.11 | 0.78 | —0.36 |
| —0.84 | 0.18 | 0.03 | —0.38 | —0.86 | —0.77 | —0.68 | —0.40 |
| —0.77 | —0.50 | —0.17 | —0.16 | —0.47 | 0.37 | —0.57 | 0.37 |

Table 2. Correlation coefficients in granitic rocks between $Fe_2O_3$ and Cr, Co (N = 15).

| | Min. value | Max. value | Std. deviation | Average (N = 15) | Correlation coefficient with $\Sigma Fe_2O_3$ |
|---|---|---|---|---|---|
| $\Sigma$ $Fe_2O_3$ % | 1.66 | 5.27 | 1.23 | 3.62 | |
| Cr ppm | 8 | 29 | 5 | 16 | 0.50 |
| Co pmm | 26 | 65 | 10 | 41 | — 0.54 |

coefficients is computed. The next step is the calculation of the eigenvalues from which the amount of factors are decided followed by a "Varimax Rotation". The Varimax Rotation gives the advantage that the individual factor values are more significant. Above the determination of the number of factors were decided. The highest number of factors are equivalent to the number of elements. It is advisable with as few factors as possible, but the number of factors must represent a good proportion of the variation in the data set. The determination of factors will

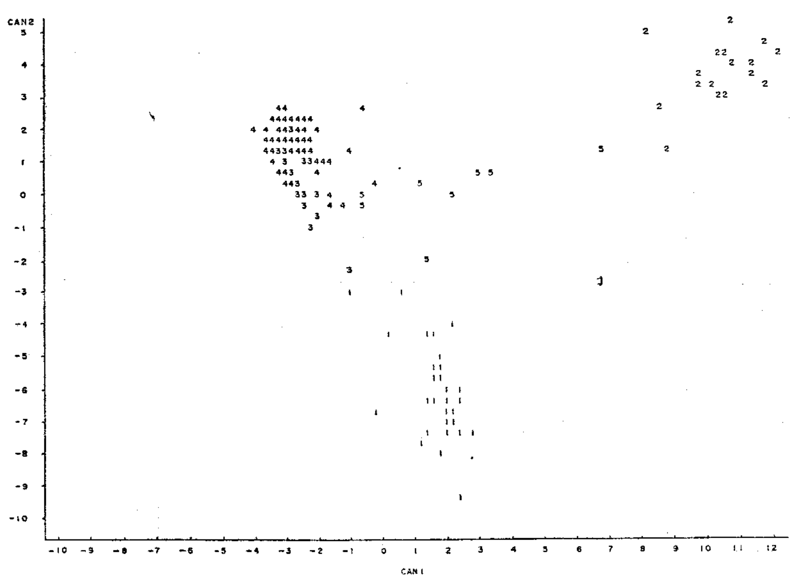


Fig. 2. Discriminant analysis given as the canonic variables Can 1 and Can 2. 1 = Host rock (serpentinite). 2 = granitic rock. 3 = Divrigi A–B Kafa iron ore. 4 = Other iron ores. 5=Attepe host rock. 45 observations are hidden (N = 160).

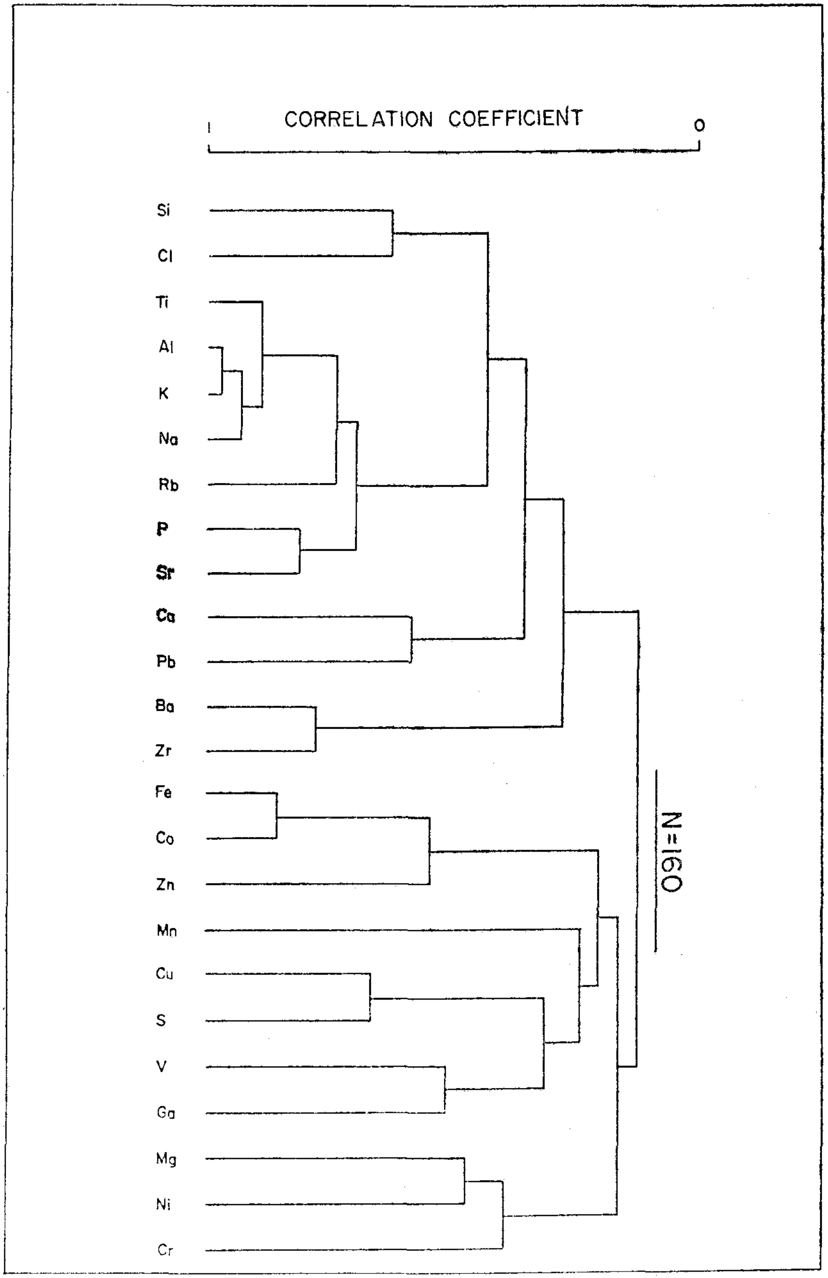


**Fig. 3. Dendrogram for all the rock samples (N = 160).**

always be a subjective choice, but the factors must characterize 70–90 % of the variation in a given population. Practical application of factor analysis can be found in Garrett & Nichol (1969), Nichol, Garrett & Webb (1969), Conradsen et al. (1976), Rossiter (1976) and Tripathi (1979).

In Table 3 an example is given how to interpretate a readout of a factor analysis. In the example 5 factors are given for a population with 160 samples. The 5 factors characterize 71 % of the variation in the data set, where the two first factors have the greatest significance with a variation of 51 % . The element association is put together linking the highest values (positive or negative).

## RESULTS OF THE MULTIVARIATE GEOSTATISTICAL ANALYSES

### *Discriminant analysis*

The analytical data comprises 24 elements from 160 samples. The predifined lithological groups are: 1) Host rocks from the A and B Kafa iron ore of Divriği including serpentinites and hydrothermal altered rocks ("Skarn", N = 33); 2) Granitic rocks from Divriği (N = 18); 3) Iron ores from A and B Kafa of Divriği region and Attepe (Feke region) –Otlukilise (N = 13), Akdağ (N = 10), Karahalka (N = 11), Bizimisen (N = 10), Kurudere (N = 10), Sultanmurat (N = 4), Akuşağı (N = 5) and Attepe (N = 13); 5) The last group is a small group from Attepe including host rocks to the Attepe iron ore. Apart from the discriminant analyses this group will not be further mentioned (N = 8) (location of the above mentioned occurrences please conference Ünlü & Stendal, 1986, Fig. 1).

The mathematic discriminant analysis should confirm if the predefined groups were reasonable or not. In Fig. 2 the diagram with the canonical variables – Can 1 versus Can 2 shows that there are 4 groups clearly separated. This is group 1 (serpentinites), Group 2 (granitic rocks), Group 5 (Attepe host rocks) and the groups 3 and 4 are gathered together, which both are iron ores and it is not surprising that they cluster together.

### *Cluster analysis*

The cluster analysis is first carried out as one population for all samples and thereafter four of the defined groups are treated individually.

Table 3. Factor coefficients for 5 factors, eigenvalues and element associations ($N = 160$).

| | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Factor 5 |
|---|---|---|---|---|---|
| $SiO_2$ | 0.73 | −0.57 | 0.09 | 0.00 | −0.04 |
| $TiO_2$ | 0.87 | −0.01 | 0.22 | −0.01 | −0.02 |
| $Al_2O_3$ | 0.95 | −0.02 | 0.15 | −0.05 | 0.02 |
| $\Sigma Fe_2O_3$ | −0.55 | 0.76 | −0.28 | −0.02 | 0.07 |
| Mn O | −0.23 | 0.04 | 0.10 | −0.71 | −0.13 |
| Mg O | −0.21 | −0.89 | −0.09 | 0.23 | −0.16 |
| Ca O | 0.14 | −0.12 | 0.87 | 0.01 | 0.02 |
| $Na_2O$ | 0.88 | −0.02 | 0.06 | −0.07 | −0.12 |
| $K_2O$ | 0.93 | −0.05 | 0.01 | −0.04 | 0.00 |
| $P_2O_5$ | 0.68 | −0.04 | 0.51 | 0.02 | −0.15 |
| Cu | −0.12 | 0.16 | 0.02 | 0.08 | 0.81 |
| Zn | −0.35 | 0.11 | 0.13 | −0.11 | 0.10 |
| Pb | −0.04 | 0.01 | 0.06 | 0.06 | −0.06 |
| Ni | −0.31 | −0.25 | 0.07 | 0.70 | −0.10 |
| Co | −0.57 | 0.71 | −0.22 | 0.17 | 0.11 |
| V | 0.00 | 0.56 | 0.16 | 0.57 | −0.17 |
| S | −0.18 | 0.16 | 0.37 | 0.35 | 0.48 |
| Cr | −0.32 | −0.76 | −0.18 | 0.27 | −0.16 |
| Ba | 0.24 | 0.00 | −0.15 | −0.25 | 0.57 |
| Sr | 0.66 | 0.00 | 0.47 | −0.05 | −0.07 |
| Zr | 0.92 | 0.02 | −0.04 | −0.10 | 0.12 |
| Ga | −0.16 | 0.89 | −0.25 | 0.17 | 0.03 |
| Rb | 0.67 | −0.03 | −0.11 | 0.09 | 0.06 |
| Cl | 0.53 | −0.45 | −0.15 | 0.20 | 0.06 |
| Eigenvalues | 8.29 | 3.87 | 1.95 | 1.61 | 1.31 |
| Proportion | 0.35 | 0.16 | 0.08 | 0.07 | 0.05 |
| Cumulative | 0.35 | 0.51 | 0.59 | 0.66 | 0.71 |
| Element association | Al, K, Zr, Na, Ti, Si, P, Rb, Sr versus Fe, Co | Ga, Fe,Co versus Mg, Cr | Ca | Ni, V versus Mn | Cu, Ba. |

The basis for the cluster analysis is the correlation analysis. In Fig. 3 the R–mode dendrogram for all samples is given showing three clusters. In Fig. 3–4, Table 4–5 and the following paragraphs only the elements are given – e.g. all the major elements are not written as oxides ($Al_2O_3$, $SiO_2$, $K_2O$ a.s.o.), but only as Al, Si, K and so on. The analytical value used is the oxide value for major elements. Group 1 (Fig. 3) represents Al, K, Na, Ti, Rb, P, Sr, Si, Cl, Ca, Pb, Ba, Zr, which mostly are lithophile elements from the granitic rocks and eventually granitic influence on some host rocks. This influence might also be a hydrothermal alteration of the serpentinites (earlier called skarn, Klemm 1960). The second element association is Fe, Zn, Cu, S, V, Ga, Mn representing siderophile– and chalcophile elements. This association reflects the iron ores and a typical sulphide paragenesis, which commonly is a late hydrothermal phase overprinting the iron ores. The third association is Mg, Ni, Cr representing the ultrabasic rocks (serpentinites).

The cluster analysis has also been carried out on the individual rock units even though they represent a small amount of samples (Fig. 4 and Table 4). The group of host rocks (Fig. 4.1) has a complex element association with Ba, Zr, Rb, Al, K, Ti, P, Ca, Sr, V, Ga and Na, which is influenced by hydrothermal alteration, serpentinisation or granitic overprinting. The second association is the typical ultramafic with Mg, Ni, Cr (serpentinite).

The granitic group has only 18 samples from which 3 are gabbroic in composition. This gives two significantly divided groups. The first association represents the gabbroic rocks with Cr, Ni, Ca, Mg, V, P, Mn, Fe and Ti. The granitic rocks comprise the elements K, Rb, Si, Na, Ba, Ga and Zr.

The Divriği iron ore contains mostly of magnetite. The variation the element distribution is a question of different generations of alteration and / or remobilization of minerals and not a question of different lithological groups. The interpretation is therefore a bit different, thus it is necessary to combinate field observations and microscopic studies of the ores together with the element association.

The first element association in the Divriği samples is Mg, K, Al, Si, Rb, Na and Cl representing a silicate phase, which occurs as inclusions in primary magnetite, but only in the first generation of magnetite (A–Kafa) or it might be hydrothermal alteration of the iron ore and serpentinites, commonly seen in B–Kafa. All the other element associations

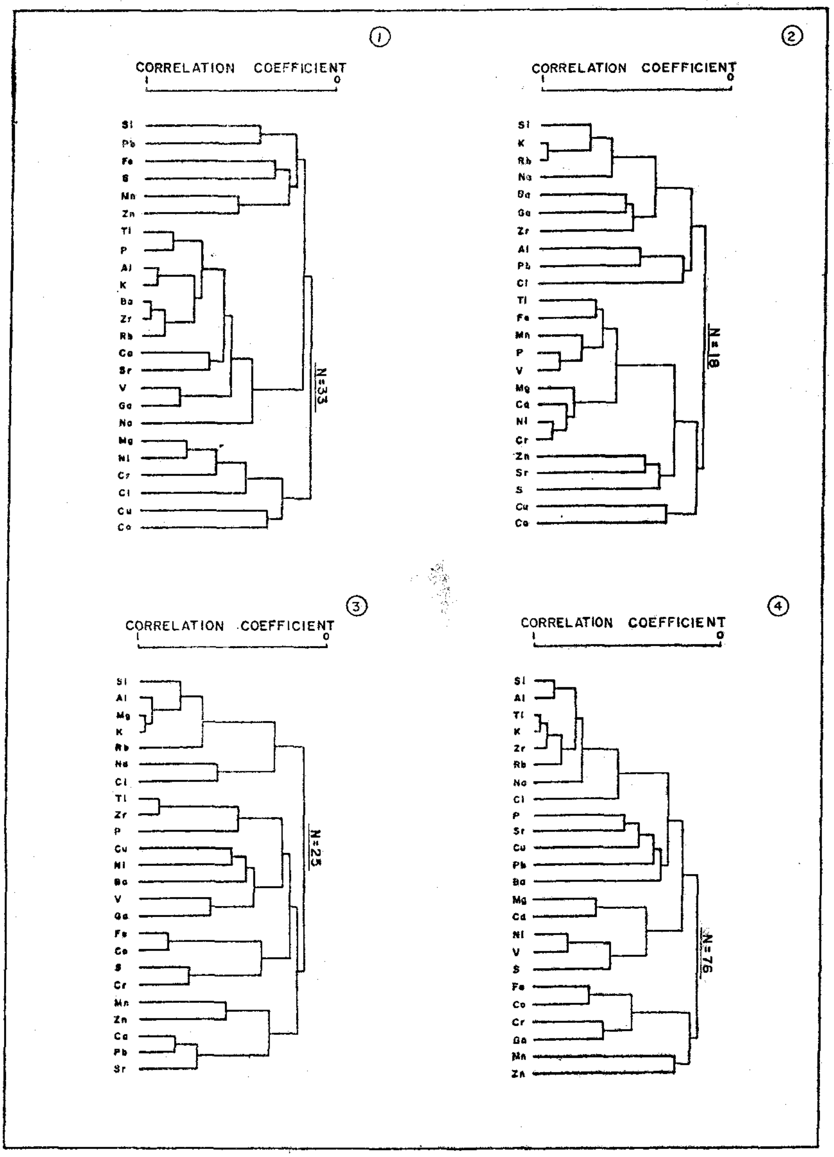


Fig. 4. Dendrogram for the individual groups of rocks. 1, 2, 3, 4 please cf. Fig. 2.

Table 4. Element association and interpretation of the cluster analysis.

| Group | Element Associationen | Interpretation |
|---|---|---|
| All samples<br>N = 160 | 1. Al, K, Na, Ti, Rb, P, Sr, Si, Cl, Ca, Pb, Ba, Zr<br>2. Fe, Co, Zn, Cu, S, V, Ga, Mn<br>3. Mg, Ni, Cr | Granitic rocks and hydrothermal alteration.<br>Paragenesis of sulfide.<br>Serpentinite. |
| Host rock<br>N = 33 | 1. Ba, Zr, Rb, Al, K, Ti, P, Ca, Sr, V, Ga, Na<br>2. Mg, Ni, Cr | Hydrothermal alteration of serpentinite (granitic influence?) or serpentinization.<br>Serpentinite. |
| Granitic rock<br>N = 18 | 1. Cr, Ni, Ca, Mg, V, P, Mn, Fe, Ti<br>2. K, Rb, Si, Na, Ba, Ga, Zr | Gabbroic rock.<br>Granitic rock. |
| Divriği<br>A + B Kafa<br>Ores<br>N = 25 | 1. Mg, K, Al, Si, Rb, Na, Cl<br>2. Fe, Co, Cr, S<br>3. Ti, Zr, P, V, Ga, Cu, Ni, Ba<br>4. Ca, Pb, Sr, Zn, Mn | Phase of silicates in magnetite or hydrothermal alteration of the ore.<br>Paragenesis of sulfide-ultra mafic rock.<br>Paragenesis of sulfide-mafic rock.<br>Paragenesis of sulfide-hydrothermal reaction with limestone. |
| Other iron ores<br>N = 76 | 1. Ti, K, Zr, Rb, Si, Al, Na, Cl<br>2. Ni, V, S, Mg, Ca<br>3. Fe, Co, Cr, Ga, Mn, Zn<br>4. P, Sr, Cu, Pb, Ba | Phase of silicate in magnetite or hydrothermal altered rock.<br>Paragenesis of sulfide in mafic rock.<br>Paragenesis of ultra mafic rock.<br>Sedimentary affinity in some iron ores and/or the last hydrothermal activity in others. |

reflect sulphide paragenesis and/or hydrothermal phases. The Fe, Ca, Cr and S association and the Ti, Zr, P, V, Ga, Cu, Ni and Ba are both ultramafic to mafic elements, which give the sulphide minerals we know from the microscopic investigation. The last association Ca, Pb, Sr, Zn and Mn is an example of mobile elements from hydrothermal reaction with the limestones. The other iron ore group has similar element association as the Divrigi iron ore group (Table 4). The samples represent different iron types, which can be deduced from the 4th element association (P, Sr, Cu, Pb, Ba,) where the sedimentary iron ores are seen. The Ba content is relatively high in this type, but Ba might also reflect a possible late hydrothermal phase in the iron ores as baryte veins (e.g. Karahalka; Pınarbaşı–Kayseri).

## *Factor analysis*

The results of the factor analysis are given in Table 5. In the population with all samples the element associations reflect the different lithological units–granitic rock, ore and serpentinite. When a smaller amount of equal samples is calculated the interpretation is different resulting in reflection of many phases or alteration of the individual rock group. The host rock shows hydrothermal alteration, serpentinization and ores in the factor analysis. The granitic rocks shows similar trend as the cluster analysis, namely the difference between the gabbroic rocks and granitic rocks. In the Divriği iron ores we have the same picture as the cluster analysis with a silicate phase and magnetite and hydrothermal processes. The Zr, Ti, V association is probably mafic rocks, which earlier was mentioned as skarn. The mixed iron ore group has in the first factor a division between magnetite and silicate. The second association is pure magnetite ore and the third association representing sulphide parageneses.

Table 5. Element association and interpretation of the factor analysis.

| Group | Element Associationen (Factors) | Interpretation |
|---|---|---|
| All samples<br>N = 160 | 1. Al, K, Zr, Na, Ti, Si, P, Rb, Sr versus Fe, Co<br>2. Ga, Fe, Co versus Mg, Cr<br>3. Ca | Granitic rock and magnetite ore.<br>Magnetite ore in serpentinite.<br>Not explainable. |
| Host rock<br>N = 33 | 1. Al, K, P, Ba, Ti, Zr, Rb, Na, V versus Ni, Mg, Cr<br>2. Fe, Ga, Co versus Si<br>3. Cl, Cr, Mg, Ni versus Ca, Pb | Hydrothermal alteration of serpentinite (granitic influence?) or serpentinization.<br>Magnetite ore.<br>Hydrothermal alteration in serpentinite. |
| Granitic rock<br>N = 18 | 1. V, Mn, Ti, Fe, P, Mg, Cr, Ca, Ni versus Si, Na, Rb, K<br>2. Ga, Ba, K, Rb versus Cr, Ni<br>3. Al, Cl, Pb versus Co | Gabbroic rock and granitic rock (Si, Na, Rb, K).<br>Distinguishing between granitic rock and gabbroic rock.<br>Distinguishing between granitic rock and gabbroic rock. |
| Divriği A + B Kafa Ores<br>N = 25 | 1. K, Mg, Al, Si versus Co, Fe, Cr<br>2. Zr, Ti, V<br>3. Sr, Ca, P, Pb versus Ga | Phase of silicates and iron ore.<br>Gabbroic rock or hydrothermal alteration ("Skarn").<br>Sulfide of hydrothermal origin. |
| Other iron ores<br>N = 76 | 1. K, Ti, Zr, Al, Si, Rb, Na versus Co, Fe<br>2. Cr, Fe, Ga versus Mg, Ca<br>3. V, Ni, S versus Mn | Phase of silicates together with Magnetite or hydrothermal altered rock.<br>Magnetite ore.<br>Paragenesis of sulfide. |

## DISCUSSION

The multivariate geostatistical analyses have given us a geochemical interpretation of the Divriği area. Cluster–and factor –analysis have grouped the data in different element associations, which can be interpreted in different ways. The two methods give approximately the same results, thus the following covers a general interpretation contemporaneously with our knowledge to the geology and the microscopic investigations.

The massive magnetite ore has one phase, where the magnetite has many inclusions of silicates (e.g. A–Kafa in Divriği). The next step is a division of the silicate and magnetite to a pure magnetite. This magnetite is common and geochemically a division of Cr, Fe versus Si is seen in the geostatistically analyses.

Primary magnetite is known from serpentinized ultra–mafic rocks (host rocks) as disseminated grains together with chromite, which also is documented in Bayhan (1980). The division of Fe and Cr to secondary magnetite in serpentinites yield a negative correlation between these elements (Table 1). The serpentinization effect shows geostatistically a phase with Fe versus Mg, Cr and Ni.

The hydrothermal events cause different element associating of the mobile elements. The hydrothermal phases give alterations of the host rocks and / or precipitation of sulphide minerals of Fe, Co, Ni, Cu all mobilised from the mafic to ultramafic rocks. Alteration of host rocks and ores and newly formed sulphide minerals is clearly observed in Divriği B–Kafa. But primary sulphides of Fe, Cu, Ni, Co have also been found in the ultramafic rocks.

The light mobilized granitic elements occur in serpentinized rocks. It is difficult to say what role the granitic rocks had played during the ore formation, but from the field relationships, the microscopic studies and the geochemical analyses the iron ore and the granitic rocks are clearly separated. The granitic rocks might give heat to a hydrothermal circulation system, but not as the base for the primary iron ores as postulated in Klemm (1960) and Kosal (1973) or with more simple words– "Skarn formation". The chemistry of the iron ores are closely related to mafic and ultramafic rocks. Another model is given by Köprübasi (1985) and Tokel & Köprübasi (1986), who interpetrate the Fe–bearing silicates in ultramafic rocks and in the granitoids as being dissolved by Cl–bearing solutions from the granitoids. However, the present investigation shows that the relationship between Fe and the chemistry of mafic – to ultramafic rocks are closely related to serpentinization processes.

## CONCLUSION

As concluding remarks the following paragraphs summarize the investigations:

1) The multivariate geostatistical methods is calculated on different rocks (N = 160) from the Divriği region. The methods used are discriminant analysis, cluster analysis and factor analysis.

2) The discriminant analysis with canonical discrimination divided the population in different rock groups.

3) The cluster analysis gave first the element association for the whole population divided into granitic rocks, sulphide paragenesis and serpentinites . The individual rock groups were divided in different element associations representing different processes e.g. hydrothermal alteration or mineral parageneses.

4) The factor analysis gave similar results as the cluster anlaysis, but with the factors it is possible to divide the element association in positive or negative factor coefficients (elements).

5) The multivariate geostatistical analysis gives an indication of the genesis of the iron ores in the Divrigi region. The interpretation of the magnetite ore is a provenance from the serpentinization of mafic to ultramafic rocks followed by several hydrothermal phases. However, it should be emphasized that the geochemistry alone is not enough to interpretate the Divriği iron ores, and that the modelling of the genesis requires further studies of the geological relationships, including mineralogical and petrographic analyses.

## ACKNOWLEDGEMENT

The authors wish to acknowledge M.T.A. and T.D.Ç.İ. Ankara, for their support during field studies, and the NATO Science Fellowship Programme in Denmark, who has financed two field visits to Turkey (1986 and 1987) for H. St.. T.Ü. wishes to express his gratitude to the Ministries of Education of Turkey and Denmark for their supports to his stay at the University of Copenhagen. Acknowledgement also goes to Mr. L.R. Petersen, who helped with the SAS programme, and to Mr. A. Pratt for correcting the English manuscript (both at the University of Copenhagen).

REFERENCES


ALLEN, A. (ed.) 1982: SAS User's Guide: Basics, 1982 Edition. Cary NC: SAS Institute Inc., 1982, 923 p.

ALLEN, A. (ed.) 1985: SAS User's Guide: Statistics, Version 5. Cary NC: SAS Institute Inc., 1985, 956 p.

BAYHAN, H., 1980: Güneş–Soğucak (Divriği/Sivas) Yöresinin Jeolojik, Mineralojik, Petrografik–Petrolojik ve Metalojenik İncelenmesi: Doktora Çalışması, H. Ü. 188 p., Ankara (English abstract).

BELL III, H. 1976: Geochemical reconnaissance using heavy minerals from small streams in central South Carolina: US Geol. Survey Bull., 1404, 23 p.

BOOM, G. VAN DEN 1981: Auswertung geochemischer Prospektionsergebnisse: Ed. Bender, F.: Angewandte Geowissenschaften Band 1, p. 347–358, Ferdinand Enke Verlag, Stuttgart, 1981.

CLAUSEN, F.L. & HARPØTH, O. 1983: On the use of discriminant analysis techniques for classifying chemical data from panned heavy–mineral concentrates – central East Greenland: J. Geochem. Explor. 18, 1–24.

CONRADSEN,K., KNUDSEN, J.G., LARSEN,M. & SCHÖNWANDT, H.K. 1976: Multivariate statistical methods as a tool in the interpretation of heavy mineral data. A case study on statistical pattern recognition of earth data : 14 th International Symposium on the Application of Computer Methods in the Mineral Industries: Pennsylvania State University, 1–12.

DAVİS, J.C. 1973: Statistics and Data Analysis in Geology: Wiley, New York, N. Y., 550 p.

GARRETT, R.G. & NİCHOL, I. 1969: Factor analysis in the interpretation of regional geochemical stream sediment data: Q. Colo. School Mines 64, 245–264.

HESP, W.R. & RİGBY, D. 1973: Cluster analysis of rocks in the New England igneous complex, New South Wales, Australia: Ed. M. J. Jones, Geochemical Exploration 1972, The Instn Min. Metall., 221–235.

HOWARTH, R.J. & SİNDİNG–LARSEN, R. 1983: Multivariate analysis: Ed. Govett, G.J.S., Handbook of Exploration Geochemistry, Volume 2 (Ed. Howarth, R.J.), Statistics and data analysis in geochemical Prospecting, 207–289. Elsevier, Amsterdam, 1983.

KLEMM, D.D. 1960: Die Eisenerzvorkommen von Divrik (Anatolien) als Beispiel tektonisch angelegter pneumatolytisch–metasomatischer Lagerstättenbildung: N. Jahrbuch f. Min., Abh. 94, (Festband Ramdohr), 591–607, Stuttgart.

KOCH, G.S., Jr. & LİNK, R.F. 1971: Statistical analysis of geochemical data: Vol. II. John Wiley & Sons, New York, 438 p.

KOŞAL, C. 1973: Divriği A–B–C Demir Yataklarının Jeolojisi ve Oluşumu Üzerinde Çalışmalar: M.T.A. Dergisi, v. 81, 1–22, Ankara.

KÖPRÜBAŞI, N. 1985: Cürek (Divriği) Granitoidinin petrolojik ve jenetik incelenmesi: K.Ü. Fen Bilimleri Enstitüsü, Yüksek Lisans Tezi, 61 s., Trabzon.

LEPELTİER, C. 1969: A simplified statistical treatment of geochemical data by graphical representation: Econ. Geol. v. 64, 538–550.

LEVİNSON, A.A. 1974: Introduction to Exploration Geochemistry: Applied Publishing Ltd. Wilmette, III., USA, 612 p.

McCAMMON, R.B. 1974: The statistical treatment of geochemical data: Introduction to Exploration Geochemistry (in Levinson, 1974), 469-508.

NICHOL, I., GARRETT, R.G. & WEBB, J.S. 1969: The role of some statistical and mathematical methods in the interpretation of regional geochemical data: Econ. Geol. v. 64, 204-220.

OBİAL, R.C. & JAMES, C.H. 1973: Use of cluster analysis in geochemical prospecting, with particular reference to southern Derbyshire, England. Ed. M. J. Jones: Geochemical Exploration 1972, The Instn Min. Metall., 237-257.

ROSSİTER, A.G., 1976: Stream-sediment geochemistry as an exploration technique in the Westmoreland area, northern Australia: BMR J. Aust. Geol. Geophys. 1, 2, 153-170.

SINCLAIR, A..J. 1983: Univariate analysis: Ed. Govett, G.J.S.; Handbook of Exploration Geochemistry, Volume 2 (Ed. Howarth, R.J.), Statistics and data analysis in geochemical Prospecting , 59-81, Elsevier, Amsterdam, 1983.

TENNANT, C.B. & WHİTE, M.L. 1959: Study of the distribution of some geochemical data: Econ. Geol. 54, 1281-1290.

THOMPSON, M. 1983: Control procedures in geochemical analysis: Ed. Govett, G.J.S.; Handbook of Exploration Geochemistry, Volume 2 (Ed. Howarth, R.J.), Statistics and data analysis in geochemical Prospecting, 39-58, Elsevier, Amsterdam, 1983.

TOKEL, S. & KÖPRÜBAŞI, N. 1986: Doğu Anadolu'da Tersiyer Yaşlı "S" Tipi Çarpışma Granitoidleri ve Üçlü Dokanak Demir Birikimleri: Türkiye Jeoloji Kurultayı, 1986 Bildiri Özleri, 3, Ankara (English abstract).

TRİPATHİ, V.S. 1979: Factor analysis in geochemical exploration: J. Geochem. Explor. 11, 263-275.

ÜNLÜ, T. & STENDAL, H. 1986: Divriği Bölgesi Demir Yataklarının Element Korelasyonu ve Jeokimyası: Orta Anadolu, Türkiye (Geochemistry and element correlation of iron deposits in the Divriği Region, Central Anatolia, Turkey): Jeo. Müh., 28, 5-19, Ankara (English abstract).