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PAPER 79-20

USE OF DISCRIMINANT ANALYSIS TO EVALUATE COMPOSITIONAL CONTROLS OF STRATIFORM MASSIVE SULPHIDE DEPOSITS IN CANADA

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Energy, Mines and Resources Canada
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Abstract

Multiple discriminant analysis of Cu, Pb, Zn, Ag, and Au grades in Canadian stratiform massive sulphide deposits revealed that the relative grade values show a systematic variation with the geological age, environment, and chemical composition of associated volcanic rocks. In general, Pb grade decreases as deposit age increases; Zn and Ag have the opposite trend. Deposits in an essentially volcanic environment are relatively richer in Cu, whereas those in a sedimentary environment are relatively richer in Pb. Deposits associated with mafic volcanic rocks have relatively higher Cu grades and those in felsic volcanic rocks have relatively higher Pb and Zn grades.

Résumé

L'analyse discriminante multiple des teneurs en Cu, Pb, Zn, Ag et Au des gisements sulfurés massifs stratiformes au Canada a révélé que les concentrations relatives varient systématiquement avec l'âge géologique, l'environnement et la composition chimique des roches volcaniques qui y sont associées. En général, la teneur en Pb diminue au fur et à mesure que l'âge du gisement augmente, tandis que les concentrations de Zn et de Ag ont tendance à augmenter avec l'âge. Les gisements situés dans un environnement essentiellement volcanique sont relativement plus riches en Cu; ceux en milieux sédimentaires contiennent par contre relativement plus de Pb. Les gisements associés à des roches volcaniques mafiques présentent une teneur relativement plus élevée en Cu, tandis que ceux associés aux roches volcaniques felsiques contiennent relativement plus de Pb et de Zn.

INTRODUCTION

Massive sulphide deposits vary widely in relative proportions of copper, lead, zinc, silver, and gold, as well as in absolute content of these metals. General relationships between the grades and geological characteristics of the deposits have been suggested by a number of authors, and have led to a number of classification schemes. However, the procedures used in classification are in some cases very subjective and result in a high proportion of exceptions, and thus provide legitimate reasons to question the proposed relationships. The present study re-examines these relationships using what is believed to be a more objective, statistical approach, based on data for Canadian deposits (Fig. 1). To the extent that this exercise is successful, the relationships thus defined should serve to stimulate further investigation into their genetic causes, and should also be useful in mineral resource appraisals by identifying the parameters that could be used to estimate metal contents of undiscovered deposits in areas of known geology.

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PREVIOUS STUDIES

A classification proposed by Hutchinson (1973) illustrates the difficulties that can arise from subjectively grouping these deposits of massive sulphide type. He recognized three types of massive sulphide deposits distinguished by their ore compositions, rock associations and age. He concluded that a zinc-copper type of massive sulphide deposit tends to occur in differentiated, mafic to felsic volcanic rocks; a lead-zinc-copper-silver type tends to occur in more felsic, calc-alkaline volcanic rocks; and a copper-iron (cupreous pyrite) type occurs in mafic, ophiolitic volcanic rocks. He noted that deposits of the first class are most numerous and best developed in Archean greenstone belts; the second class (rare in the Archean) occurs in the Proterozoic and Phanerozoic; whereas his cupreous pyrite type is most common in ophiolitic sequences in the Phanerozoic. Hutchinson's choice of terminology for his different types of deposits may be unfortunate because, due to the subjective nature of his method of classification, his grouping of deposits as chemical types is not as exclusive in terms of metal contents as his terminology would suggest. For example, as he noted (p. 1240-1241), some of the Cyprus deposits, although classified as cupreous pyrite deposits, are in fact zinc-rich and are included in this class mainly on the basis of their association with mafic, ophiolitic rocks. This also means that the association of a particular chemical type with a particular volcanic lithology is a questionable generalization. In addition to the zinc-bearing Cyprus deposits, the York Harbour (Duke and Hutchinson, 1974) and Betts Cove (Upadhyay and Strong, 1973) deposits of Newfoundland, those near Tottenham and Girilambone, New South Wales (Scheibner and Markham, 1976), and at Weiss, Turkey (Hutchinson, 1973) occur in mafic, ophiolitic volcanic rocks but are of the copper-zinc type and are not of the cupreous pyrite type as one would infer from Hutchinson's classification.

The age restriction suggested by Hutchinson (1973) for his deposit types is also less distinct than he implied. Deposits of lead-zinc-copper type which he noted as rare or absent in the Archean, are perhaps not that rare. The Coniagas (1% Pb, 10.77% Zn), Sturgeon Lake (Boundary) (1.09% Pb, 5.17% Zn, 1.18% Cu), Indian Mountain Lake (1% Pb, 10% Zn) and Hackett River (1.5% Pb, 8.15% Zn, 0.25% Cu) deposits of Canada and the Big Stubby barite-lead-zinc-silver deposits of Australia (Sangster and Brook, 1977; Lipple, 1976) provide some notable examples of the lead-zinc-copper type in the Archean. In fact Pidgeon (1978) has recently obtained an age of 3450 Ma for the Big Stubby deposits.

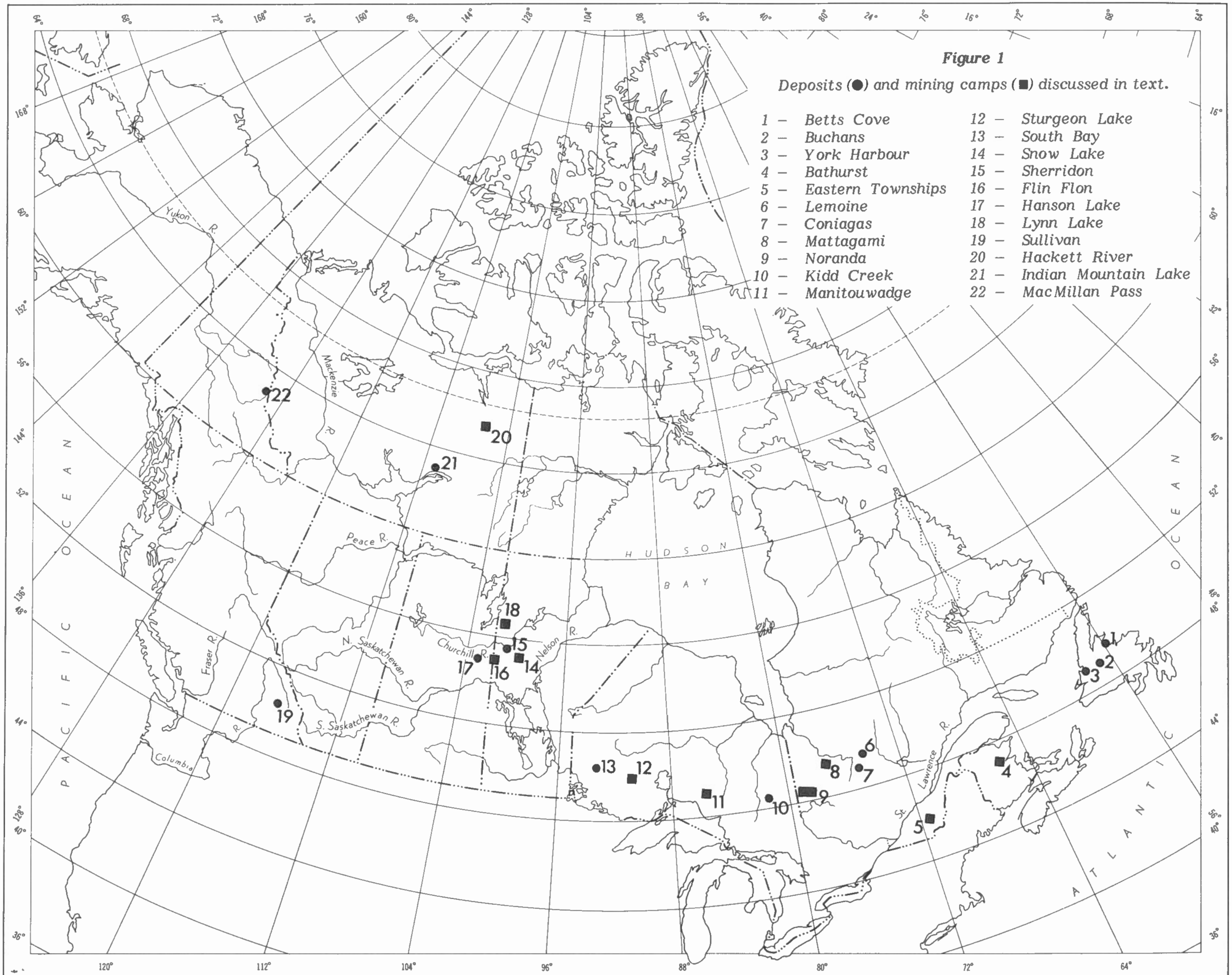

Figure 1

Deposits (●) and mining camps (■) discussed in text.

Although Hutchinson considered a possible Aphebian age for the zinc-copper deposits of the Flin Flon, Manitoba, and Jerome, Arizona, areas, he concluded that there was not sufficient evidence for this age and preferred that the age of these deposits be regarded as Archean so they would best fit his scheme of classification. However, the K-Ar and Rb-Sr data (Giletti and Damon, 1961; Livingston and Damon, 1968; Lanphere, 1968) and model lead ages (Mauger et al., 1965) indicate a Proterozoic age for the Arizona deposits. As summarized by Sangster (1972a), zircon U-Pb ages for the host rhyolites of the United Verde, Iron King and Old Dick deposits are 1820 ± 10 Ma, 1775 ± 10 Ma, and 1760 Ma, respectively (Anderson et al., 1971; Silver, 1966), and it is very difficult to accept these ages as due to updating during metamorphism. A Proterozoic age for these deposits is now generally accepted (Dewitt, 1978). Evidence for an Aphebian age for the Flin Flon deposits will be presented later in discussing ages of deposits included in this study.

It must also be noted that the Flambeau (Ladysmith), Pelican River and Crandon massive sulphide deposits in Wisconsin are considered to be of Aphebian age (Mudrey et al., 1977; Wiggins and Brett, 1977). This age assignment is supported by model lead ages for the first two deposits (Sims, 1976) and by zircon U-Pb ages on correlative volcanic rocks (Banks and Rebello, 1969; Van Schmus et al., 1975). When these deposits in Manitoba-Saskatchewan, Arizona and Wisconsin, almost exclusively of the copper-zinc type and including the large Flin Flon, Manitoba, and Crandon, Wisconsin, orebodies, are all assigned to the Aphebian rather than the Archean, one is left with considerable doubt as to the existence of any age-dependent compositional trend in massive sulphide ores.

Fox (1976) suggested that the composition of the ores reflect the wall rock compositional trends, copper-rich ores low in lead, and apparently enriched in iron, are in tholeiitic and "transitional" volcanic sequences, and ores rich in Pb + Zn are in calc-alkaline volcanic sequences. Solomon (1976) subdivided "volcanic" massive sulphide deposits into zinc-lead-copper, zinc-copper, and copper types on the basis of their overall copper/lead/zinc ratios and attempted to determine if the ore types are associated with specific types of host rocks. For 50 deposits, the rocks for 100 m into the stratigraphic footwall were classified as felsic volcanic (rhyolite and dacite), mafic volcanic (basalt and andesite), or sedimentary. The zinc-lead-copper deposits have predominantly felsic volcanic or mixed felsic volcanic-sedimentary footwall lithologies, and the copper deposits show a preference for mafic volcanic or mixed mafic volcanic-sedimentary footwall lithologies. However, the deposits of zinc-copper type have both felsic volcanic and mafic volcanic footwall rocks. For most of the associations considered by Solomon (1976) distinct relationships are lacking and only in the case of the zinc-lead-copper deposits in his sample is the correlation convincing since 70 per cent of these deposits were found to have only felsic volcanic rocks (half including some sedimentary rocks) in the stratigraphic footwall and 92 per cent have abundant rhyolites in the footwall. Also, he noted that lead is almost invariably associated with felsic rocks and never with ophiolitic terranes, and that Archean deposits are generally very low in lead.

Sangster and Scott (1976, p. 173) noted that in metal ratio, grade, and other features, massive sulphide orebodies in mixed volcanic-sedimentary environments more closely resemble those in purely volcanic environments than those in purely sedimentary environments.

Sangster (1977) examined the relationship of grades with age and tonnage of Canadian deposits. No distinct correlations were found between size of the deposits and their zinc or copper grades. Phanerozoic deposits were found to be richer in lead than Precambrian deposits, and to show a good correlation between zinc and lead, but an antipathetic relationship between lead and copper. Copper and zinc grades in massive sulphide deposits were found to vary independently of each other. These relationships, and tonnage distribution and mean grade information also supplied by Sangster (1977), are of value in resource prognostication, but did not take into account lithologic characteristics of the deposits.

Thus the interrelationships suggested by previous studies are neither as specific nor as rigorously defined as would be desirable for utilizing these correlations in defining or evaluating proposed genetic models, or as an aid in resource prognostication.

The present study forms part of a continuing program by the Geomathematics Section of the Geological Survey of Canada to develop methods of regional resource appraisal. In this regard the aim of the study is to identify some of the geological features that must be considered in estimating the metal potential of areas containing submarine volcanic rocks.

DEPOSIT MODELS

Stratabound massive sulphide deposits in Canada occur in rocks of varied geological environments ranging in age from Archean to Cenozoic (Sangster and Scott, 1976). In resource appraisal studies, a common approach is to use wall rock compositions and (overall) geological settings to define a deposit model. A very large group of Canadian deposits occurs in submarine volcanic rocks. These deposits are considered to be genetically related to volcanic rocks and are called volcanogenic massive sulphide deposits (Sangster and Scott, 1976). For these deposits we prefer the volcanic-exhalative genetic model which advocates that the ores are an integral part of, and coeval with, the volcanic complex in which they occur. Sangster and Scott (1976, p. 200) have ably summarized the evidence that favours such a genesis, and which militates against an epigenetic origin. The concept of metal solution and transport (Solomon, 1976; Hodgson and Lydon, 1977; Lydon, 1978) in systems comparable to recently well-studied geothermal systems suggests that the ore metals may be leached by brines from rocks some distance in the stratigraphic footwall; however, pending further evidence, we wish to reserve judgement as to whether or not there may be a significant metal contribution from a magmatic source.

METHODS OF STUDY: DISCRIMINANT ANALYSIS PROCEDURE

In order to re-evaluate, and to some extent quantify, the suggested relationships between metal grades and geological features of Canadian deposits, the method used is essentially the reverse of that used by Solomon (1976). The method consists of setting up classes based on 1) age, 2) geological environment of the ore deposits, and 3) composition of associated volcanic rocks; and by the use of discriminant analysis, testing whether the compositions of the ore deposits associated with each class are significantly different. The study may be considered a more sophisticated extension, with geological parameters introduced, of the study by Sangster (1977).

The data base for the study consists of the grade characteristics and general geological features of 201 Canadian stratiform massive sulphide deposits (Appendix 1), updated in 1976 from data compiled by Thorpe (1974). It is essentially the same data base as that used by Sangster (1977), and includes all Canadian deposits for which representative grade and tonnage data were available as of June 1976. Included are producers, past producers, and well-explored prospects. Data on copper, lead, zinc, silver, and gold grades are available for these deposits, although for a few deposits (many deposits in the case of lead data) low grades are not reported (e.g. <0.5% Pb and Zn, <0.01 oz/ton Au and <0.1 oz/ton Ag). Most of the grade and tonnage data are taken from published articles in mining journals, company reports, or the Canadian Mines Handbook (1976). Geological data have been obtained from published reports and field visits.

A number of problems are inherent in such a study. Geological descriptions of deposits are commonly inadequate, and the interpretation of original lithologies for some highly metamorphosed deposits can be difficult and somewhat subjective. A further problem, to obtain representative grade data for deposits, is related to the characteristics of this type of deposit (Sangster, 1972b). Alteration or feeder pipes (stringer zones) that underlie proximal deposits are generally cupriferous but of low grade, and mining limits are commonly determined by economic factors only. Thus in some deposits significant parts of copper-rich stringer zones are mined with and combined with the conformable massive ore in the overall grade figures for these deposits, whereas in other deposits such stringer zones are too low in grade to be included in the ore category. Likewise for distal deposits, i.e. those deposited at some distance from their feeder vents, the grade data apply to massive ore only since associated stringer ores are not present. Proximal and distal deposits were not distinguished in the present study because the necessary information is unavailable for many deposits, nor were attempts made to recalculate deposit grades eliminating the known stringer ores. Our results are consequently slightly biased, but we do not believe that the effect is major.

A further problem lies in deciding which rocks are to be considered as associated with an orebody, and the stratigraphic thickness over which association is considered to exist. Ideally, in accord with our preference for the volcanic-exhalative genetic model, only lithologies in a stratigraphic footwall position should be considered and these might be considered on two alternative scales, say 200 m and 2000 m into the footwall of the orebody. However, information is often lacking or very tenuous regarding stratigraphic footwall direction, so, in order not to drastically reduce our data set, lithologies for 50 to 100 m into both footwall and hangingwall have been considered in this study.

Age Parameters/Groups

Ages are fixed primarily by radiometric studies on wall rocks, or lead isotope model ages of ores. Although minor uncertainties in age exist for most deposits, virtually all are well enough established to be assigned to one of three groups – Archean, Proterozoic, or Paleozoic. The Paleozoic group consists primarily of the Appalachian deposits, typified by the Bathurst camp where deposits occur in Ordovician strata. The majority of the Proterozoic group of deposits occur in the circum-Kisseynew (Flin Flon-Snow Lake) supracrustal belt (Sangster, 1972a); these deposits are considered by us to be of Proterozoic (Aphebian) age for a number of reasons. Model lead ages of about 1750-1950 Ma for galena from the Flin Flon-Snow Lake area were reported by Sinha (1970) and Sangster (1972a, 1978). Slawson and Russell (1973) argued against a single-stage interpretation of these leads on the basis of four samples they analyzed. One of these analyses, for the Snake Lake showing, cannot be related to massive sulphide deposits of the area since the showing is reported to consist of a vein in gabbro, and two of the analyses yield single-stage ages in essential agreement with those previously reported. Their argument thus hinges on one sample, the character of which is not documented, from the Flin Flon mine, and their two-stage or three-stage interpretation has been questioned by Thorpe and Sangster (1973). The deposits of the Flin Flon area are probably older than about 1865 Ma since the Flin Flon orebody is cut by a dyke that may be correlated with the Kaminis granite and the latter has been reported to have that age (K-Ar; Wanless et al., 1965). An Aphebian age for the host Amisk volcanics is also supported by Rb-Sr isochrons at 1738 ± 90 Ma and 1780 ± 45 Ma ($\gamma^{87}Rb = 1.42 \times 10^{-11}$/yr, Mukherjee et al., 1971; Bell et al., 1975), although the similarity of these ages to that of the Hudsonian orogeny complicates their interpretation, and by preliminary U-Pb data for zircons (Stauffer, pers. comm. 1978).

Deposits of the Archean group occur primarily in the Superior and Slave geological provinces, and are 2650-2760 Ma in age on the basis of their model lead ages and U-Pb wall rock ages. The lead isotope data for galena contained in these deposits have been presented by Roscoe (1965), Kanasewich and Farquhar (1965), Ostic et al. (1967), and Thorpe (1972). Zircon U-Pb ages on host rocks have been presented by Krogh and Davis (1971), Krogh et al. (1976), Green (1968), Nunes and Thurston (1978), and Nunes et al. (1978).

Environment Parameter/Groups

The deposits have been separated into three groups, depending on the predominant lithology of the host rocks – (1) those in a predominantly volcanic environment, (2) those in a volcano-sedimentary (mixed) environment, and (3) those in a predominantly sedimentary environment. Normally, the volcanic group occurs close to a volcanic centre, marked by breccias and felsic flows, but in some areas more distal volcanic products (bedded tuffs) are characteristic of the environment. Deposits of the Noranda camp (Spence, 1975) typify those proximal to a volcanic centre, but those of Sturgeon Lake (Franklin et al., 1975) and Heath Steele, Bathurst camp (McBride, 1976) occur in a more distal facies. Deposits of the mixed volcano-sedimentary subgroup commonly occur in a zone marginal to a volcanic edifice. Volcanic rocks in this environment are usually distal pyroclastic and epiclastic types and sedimentary rocks include pelite and volcanic-derived greywacke. Deposits in the Bathurst camp of New Brunswick and the Manitouwadge camp of Ontario typify this environmental group. Deposits of the sedimentary group are in sedimentary sequences, which normally include greywacke, siltstone and possibly arkose. Some sequences are laterally very distant from volcanic centres (e.g. Sherridon in Manitoba) and others have no apparent lateral volcanic equivalents (e.g. Sullivan in British Columbia).

Volcanic Rock Parameter/Groups

Within the group of volcanic-hosted deposits, the composition of host rocks varies from basalt to rhyolite. To study the influence of associated volcanic lithology on deposit grades, the most representative lithology of both footwall and hanging wall volcanic rocks within 50 to 100 m of each deposit is considered. The deposits (from both the volcanic and the mixed environment groups) have been separated into two groups depending on the predominance (>80%) of mafic (<65% of SiO_2) or felsic (>65% SiO_2) components within the associated volcanic rocks. Deposits associated with volcanic rock lithologies that consist of both felsic and mafic strata in approximately equal portions constitute the mixed lithology group. The compositions of the volcanic rocks, in general, are either strongly bimodal or form a single mafic or felsic class, but in the vicinity of a few deposits these compositions exhibit a continuity between basalt and rhyolite.

Discriminant Procedure

An assumption in discriminant analysis is that the input variables are normally distributed. Preliminary statistical analysis indicated that the copper, lead, zinc, silver and gold grades are not normally distributed, and that all have a positive skewness. In particular, lead and gold grade distributions show extreme positive skewness. It is known that at least some metal grades follow log-normal distributions (Singer et al., 1975; Agterberg and Divi, 1978). In order to reduce the skewness, logarithmic transformation has been applied to lead and gold grade values. However, for the study of the volcanic lithology parameter, which involved a slightly different population of deposits (sediment-hosted deposits eliminated), the transformation was applied to all the metal values. The distributions in the present study are further improved by adding constants before applying the logarithmic transformation (Krige, 1961).

Discriminant analysis is a powerful technique for classifying individual cases into pre-defined populations on the basis of multivariate measurements. An excellent review of the recent developments on the subject is contained in a volume resulting from a 'State-of-the-Art' conference on discriminant analysis organized by the NATO Advanced Study Institute (Cacoullos, 1973). It is of interest to note its application for mineral exploration (Harris, 1965; Abry, 1973; Chung, 1977; DeGeoffrey and Wignall, 1971; Prelat, 1977).

The objective of discriminant analysis is to obtain a linear function (discriminant function) of the form

$$d_i = a_i X_1 + b_i X_2 + c_i X_3 + \ldots + p_i X_p$$

such that the pre-defined populations have maximum separation along the function. $X_1, X_2, X_3 \ldots X_p$ are the p discriminating variables; $a_i, b_i, c_i, \ldots p_i$ are the discriminant function coefficients; and d_i is the discriminant score. The relative magnitudes of the coefficients associated with the variables signify the relative importance of the variables in separating the populations along the discriminant function.

The number of discriminant functions to be obtained is one less than either the number of populations or the number of variables, whichever is less. In the present study two discriminant functions are obtained because the deposits are always subdivided into three populations. For each discriminant function, Wilks' lambda indicates the statistical significance, canonical correlation coefficient signifies the strength of discrimination and the eigenvalue indicates the percentage of variation explained (see Appendix 2 for further details).

The computer programs used for discriminant analysis are DISCRIMINANT of the SPSS System (Nie et al., 1975) and a program developed by Chung (1978), although results from the latter program were used only for corroboration and are not reported here.

RESULTS

The mean metal grades for each group considered under the age, environment, and volcanic lithology parameters (Table 1) suggest that differences between groups may be significant. If significant differences in grades exist between these groups, discriminant analysis should result in correctly classifying the deposits into the predefined groups (Table 2). A summary of calculated discriminant functions and related statistics is given (Table 3) for selected groupings of deposits.

Figures 2 to 9 illustrate graphically the classification of individual deposits into the chosen groups by means of calculated discriminant functions. Each deposit is represented by a point with co-ordinates that are the two discriminant scores corresponding to the first two calculated discriminant functions (Table 3). A group centroid, defined by the two mean discriminant scores, is also plotted for each of the three groups. Group centroids that are well separated in Figures 2 to 9 indicate that there are significant differences in mean grade values between groups. Furthermore, close clustering of deposit points around group centroids indicates that grade characteristics of deposits belonging to different groups are distinctly different.

Table 1

Mean grades of Cu, Pb, Zn, Ag, and Au for the groups studied

	Cu %	Pb %	Zn %	Ag oz/ton	Au oz/ton
Age Groups					
Paleozoic (61)[1]	1.079	1.223	3.451	0.926	0.015
Proterozoic (44)	2.469	0.203	3.072	0.490	0.018
Archean (83)	1.535	0.156	4.555	1.447	0.021
Environment Groups					
Volcanic (121)	1.849	0.332	4.016	1.027	0.023
Mixed (56)	1.178	0.755	3.885	1.361	0.013
Sedimentary (24)	0.815	1.608	3.216	0.866	0.009
Volcanic Lithology Groups					
Mafic (31)	2.072	0.235	2.562	0.661	0.015
Mixed (94)	1.741	0.298	4.376	1.280	0.020
Felsic (45)	1.052	1.113	4.476	1.242	0.026

[1] Numbers in parentheses indicate the number of deposits in each subdivision.

Note that for some metals there is a systematic variation in mean grade between endmember subdivisions.

Age Parameter

When grouped by geological age (see Table 3), the first discriminant function, calculated for deposits of all environments and volcanic lithologies, accounts for 85 per cent of the variation. This function is weighted primarily with positive lead contributions and negative silver and zinc contributions. This means that with change in age of the deposits the most important change in their compositions is in lead grade and there are opposite and less important changes in silver and zinc grades. A high canonical correlation coefficient (0.69) signifies the strength of this discriminant function. The group centroids, each representing the mean discriminant score for that particular group, are clearly separated on the first discriminant axis (Fig. 2). Moving in time from Archean through Proterozoic to Paleozoic, there is a corresponding 'ordered' shift of the corresponding centroids from left to right in Figure 2. In terms of deposit character, the standardized discriminant coefficient (Table 3) suggests this shift to be related to an increase in lead grade as the deposits become younger. To give an extreme example, the Archean South Bay Mine (S) with no reported lead content is plotted farthest in the negative direction of the discriminant function axis. On the other hand, the Devono-Mississippian MacMillan Pass deposit (P) with the highest lead grade of 8.1 per cent is plotted farthest in the positive direction. The zinc and silver grades show an opposite and less strong trend, i.e. they show a general increase with geological age. The MacMillan Pass deposit contains 8.4% Zn and 2.75 oz/ton Ag whereas the corresponding grades in the South Bay mine are 12.5% and 2.91 oz/ton.

The second discriminant function, with a positive weight for silver grade and a negative weight for copper grade, accounts for only 15 per cent of the variation, and is not a strong discriminator of the three groups. However, this function axis better separates the Proterozoic and Archean clusters which overlap on the first discriminant function axis. For example, both the Archean Hackett River (R) deposit and the Proterozoic Mandy (M) deposit (Flin Flon camp) are low lead and high zinc deposits, and as such could not be separated by the first discriminant function even though differences exist in silver grade. However, they are properly distinguished by the second discriminant function, on the basis of a low (0.31%) copper grade and a high (5.90 oz/ton) silver grade in the former, and a high (7.3%) copper grade and a low (1.80 oz/ton) silver grade in the latter deposit.

The classification result for the age parameter is only moderately good, with only 67 per cent of the total number of deposits being properly classified (Table 2). However, the pattern of misclassification also appears to support the correlation of age and composition of massive sulphide deposits. The age groups are ordered in a time-sequence and the results of our study imply corresponding ordered differences in metal grades and/or metal ratios. Therefore, given that a misclassification has occurred, it is logical to expect a higher probability of misclassification to the adjacent group than to the farthest group. This may be seen in Table 2, which indicates that of the 21 misclassified Paleozoic deposits, 86 per cent are wrongly classified as Proterozoic deposits and 14 per cent as Archean. In the case of the Archean deposits, all the misclassifications are to the Proterozoic group. The 10 misclassified Proterozoic deposits went partly to the adjacent Paleozoic (3 deposits) and Archean groups (7 deposits) respectively.

Investigation of the deposits that are misclassified to the farthest group or are far from the centroid of the adjacent group reveals anomalous characteristics relative to other deposits of the same mining camp or area. For example, the Proterozoic Hanson Lake (H) deposit is misclassified as a Paleozoic deposit because it has a much higher lead grade (5.8%) than the deposits of the nearby Flin Flon group. This deposit needs further investigation, as its compositional difference may result from an unusual genesis, or its environment may be considerably different from those of other deposits in the Flin Flon area.

The results obtained for the age parameter could have been influenced by a possible systematic variation of environment or lithology with age. The figures in Table 4 appear to support this possibility. To investigate, insofar as possible*, the interrelationship between environment and age, the analysis is repeated for the 118 deposits that occur in a volcanic environment only. That is, of the 188 deposits in Figure 2, the 70 deposits that occur in mixed or sedimentary environments are eliminated in Figure 3. Comparison of Figure 3 with Figure 2, and of the respective discriminant function coefficients in Table 3, indicates that the results are similar. In Figures 2 and 3, the South Bay (S), Mandy (M) and Hanson Lake (H) deposits are located in similar positions and due to similar reasons. The MacMillan Pass deposit (P) of Figure 2 does not appear in Figure 3 as it occurs in a sedimentary environment. However, the Middle Ordovician Restigouche deposit (G in Fig. 3) with 4.6% Pb, 5.9% Zn and 2.50 oz/ton Ag plots farthest along the positive direction on the first discriminant function axis.

* It should be noted, however, that because of the broad categorization of environments into volcanic, mixed or sedimentary, there could be minor sedimentary rocks in association with an increasing proportion of massive sulphide deposits in volcanic environments as the ages of the deposits decrease. Since this could be the case the possibility of change of the environmental parameter with time cannot be completely eliminated, and to do so would require more detailed quantification of associated lithologies than has been possible in this study.

Table 2

Comparison between the actual and predicted number of deposits in each subdivision (group) for the three parameters of age, environment, and volcanic lithology

No. of deposits in actual groups	No. of deposits in predicted group			Percentage of deposits properly classified
Age Groups				
	Paleo.	Prot.	Arch.	
Deposits of all environments and volcanic lithologies				
Paleo. (61)[1]	[40]	— 18 →	3	
Prot. (44)	3	[34]	7	67
Arch. (83)	0 ←	31 —	[52]	
Deposits of volcanic environment only				
Paleo. (24)	[15]	— 7 →	2	
Prot. (28)	5	[15]	8	64
Arch. (66)	1 ←	19 —	[46]	
Deposits of volcanic environment and in felsic volcanic rocks only				
Paleo. (8)	[6]	— 2 →	0	
Prot. (4)	0	[3]	1	87
Arch. (11)	0	0	[11]	
Environment Groups				
	Vol.	Mixed	Sed.	
Deposits of all ages				
Vol. (121)	[74]	— 38 →	9	
Mixed (56)	17	[21]	18	53
Sed. (24)	5 ←	7 —	[12]	
Deposits of Paleozoic age only				
Vol. (24)	[12]	6	6	
Mixed (26)	5	[13]	8	54
Sed. (11)	1 ←	2 —	[8]	
Volcanic Lithology Groups				
	Mafic	Mixed	Felsic	
Deposits of all ages and environments				
Mafic (31)	[19]	— 8 →	4	
Mixed (94)	19	[57]	18	59
Felsic (45)	5 ←	15 —	[25]	
Deposits of Paleozoic age only				
Mafic (10)	[7]	— 2 →	1	
Mixed (16)	2	[10]	4	69
Felsic (25)	1 ←	6 —	[18]	
Deposits of Paleozoic age and volcanic environment only				
Mafic (6)	[6]	0	0	
Mixed (10)	1	[8]	1	92
Felsic (8)	0	0	[8]	

[1] The number of deposits in each subdivision are in parenthesis.

Numbers representing correctly classified deposits are enclosed in squares.

Other numbers represent misclassified deposits and arrows connect groups with progressively fewer misclassified deposits.

The arrows are thus presumed to indicate decreasing probability of misclassification.

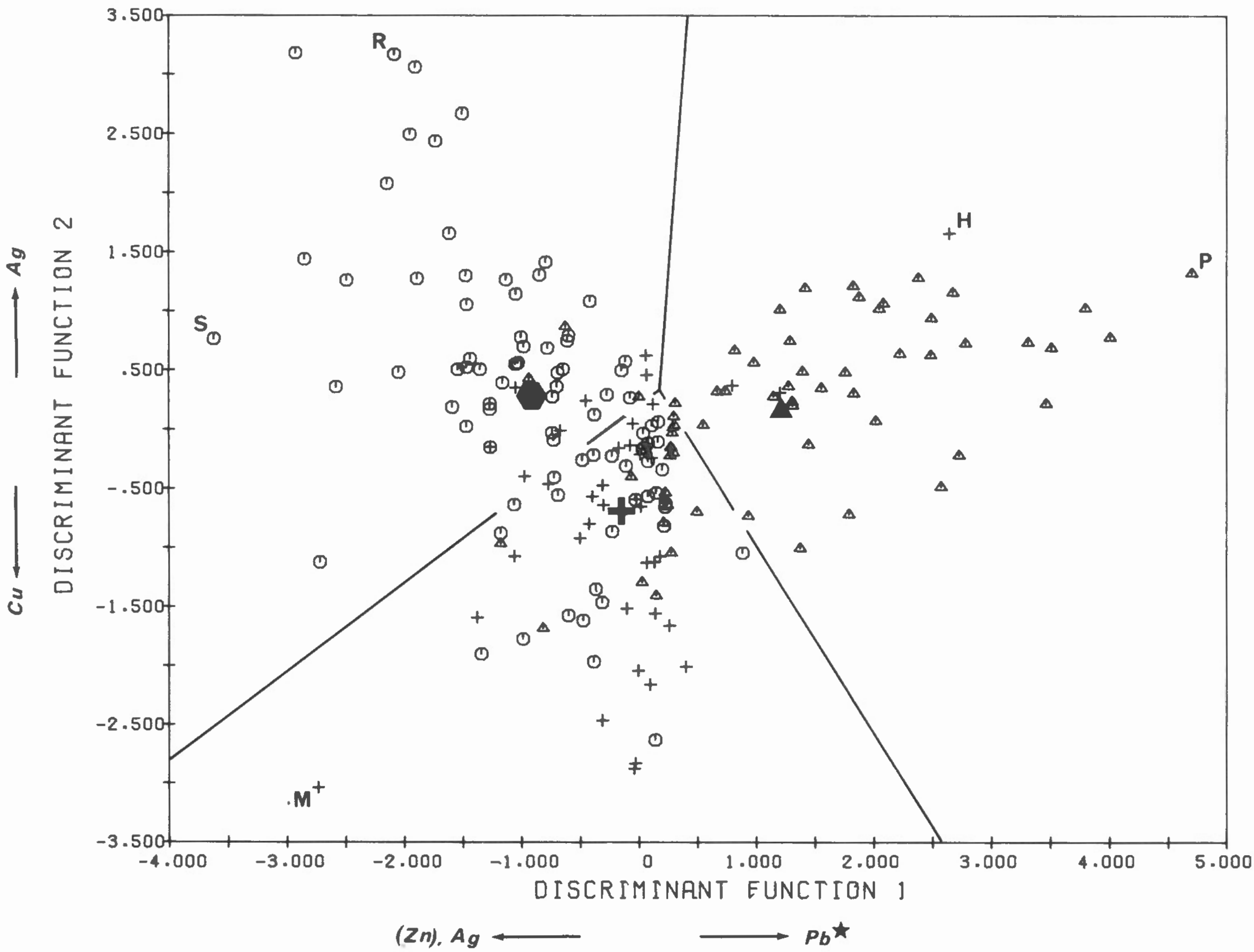

Figure 2. Plot of discriminant scores for 188 deposits subdivided into three age groups. Letters indicate individual deposits mentioned in the text. △ Paleozoic deposits; ✚ Proterozoic deposits; ⬡ Archean deposits. Group centroids are indicated by respective symbols in heavier outline. Solid lines separate group territories. Relative magnitudes of weights associated with the metals are indicated as dominant (*), moderate and low (in parenthesis).

It will be shown later that the volcanic lithology parameter has an influence on deposit grades. Therefore, the influence of the age parameter, independent of environment and volcanic lithology, on deposit grades is tested for the 23 deposits that occur in a volcanic environment and are associated with felsic volcanic rocks (Fig. 4). Proper classification improved to 87 per cent (Table 2), and the coefficients of the only significant discriminant function that accounts for 85 per cent of the variation indicate that lead grade increases and silver and zinc grades decrease as age of deposit decreases. The test could not be repeated for the deposits associated with mafic volcanic rocks because of the small number of such deposits in each of the three age groups.

Environment Parameter

In Figure 5, there is an ordered separation of the centroids belonging to the volcanic, mixed and sedimentary groups on the basis of the first discriminant function. The discriminant coefficients (Table 3) indicate that, primarily, lead grade in deposits increases from left to right corresponding to an increase in the sedimentary component. To a lesser degree, copper and zinc grades increase from right to left in Figure 5, corresponding to an increase in the amount of the associated volcanic component. For example, whereas the copper-rich (7.3%) and zinc-rich (12.9%) Mandy deposit (M) is plotted farthest along the negative direction of the first discriminant function, the lead-rich (5.8%) Sullivan deposit (S) in contrast is plotted farthest along the positive direction. Some deposits with anomalous characteristics are misclassified to the farthest group and removed far from their group centroid. For example, unlike the rest of the deposits in the Bathurst camp, the Restigouche Mining (3rd Portage Lake) deposit (R in Fig. 5) has a high content (5.8%) of lead and a low content (0.31%) of copper. Therefore, it is misclassified into the sedimentary group. Similarly, the Lemoine deposit (L) with high zinc (10.8%) and copper (4.5%) is far removed from its group (mixed environment) centroid and is misclassified into the volcanic group.

Table 3

Standardized discriminant function coefficients associated with Cu, Pb, Zn, Ag, and Au grade variables that were used to compute the discriminant function scores, and related statistics

		Discriminant Function 1	Discriminant Function 2
Age Groups			
Deposits of all environments and volcanic lithologies (Fig. 2)			
Eigenvalue		0.89474	0.15761
% of variation explained		85.0	15.0
Canonical correlation		0.68719	0.36899
Wilks' Lambda		0.45592**	0.86385**
Coefficients	Cu	-0.07956	-0.80687
	Pb	1.57395	-0.09979
	Zn	-0.52722	-0.00339
	Ag	-0.85751	0.59709
	Au	0.17286	-0.09999
Deposits of volcanic environment only (Fig. 3)			
Eigenvalue		0.49189	0.12557
% of variation explained		79.7	20.3
Canonical correlation		0.57420	0.33401
Wilks' Lambda		0.59551**	0.88844**
Coefficients	Cu	0.06339	-0.92012
	Pb	1.39809	0.13475
	Zn	-0.40859	-0.29877
	Ag	-0.89319	0.33479
	Au	0.12117	-0.14625
Deposits of volcanic environment and felsic volcanic rocks only (Fig. 4)			
Eigenvalue		2.67614	0.48659
% of variation explained		84.6	15.4
Canonical correlation		0.85321	0.57212
Wilks' Lambda		0.18299**	0.67268 (n.s.)
Coefficients	Cu	-0.14913	
	Pb	3.03721	
	Zn	-0.41147	
	Ag	-1.79037	
	Au	0.60807	
Environment Groups			
Deposits of all ages (Fig. 5)			
Eigenvalue		0.30390	0.02771
% of variation explained		91.6	8.4
Canonical correlation		0.48277	0.16419
Wilks' Lambda		0.74625**	0.97304 (n.s.)
Coefficients	Cu	-0.34365	
	Pb	1.04520	
	Zn	-0.50225	
	Ag	-0.23633	
	Au	-0.24240	

		Discriminant Function 1	Discriminant Function 2
Environment Groups			
Deposits of Paleozoic age only (Fig. 6)			
Eigenvalue		0.28809	0.07908
% of variation explained		78.5	21.5
Canonical correlation		0.47292	0.27071
Wilks' Lambda		0.71945*	0.92672 (n.s.)
Coefficients	Cu	-0.92811	
	Pb	0.22710	
	Zn	-0.57139	
	Ag	0.38836	
	Au	-0.47392	
Volcanic Lithology Groups			
Deposits of all ages and environments (Fig. 7)			
Eigenvalue		0.17926	0.09447
% of variation explained		65.5	34.5
Canonical correlation		0.38989	0.29379
Wilks' Lambda		0.77479**	0.91369**
Coefficients	Cu	-0.08626	0.33429
	Pb	0.97096	0.66585
	Zn	0.24192	-0.50679
	Ag	-0.10158	-0.69199
	Au	0.19773	0.17503
Deposits of Paleozoic age only (Fig. 8)			
Eigenvalue		0.72362	0.15895
% of variation explained		82.0	18.0
Canonical correlation		0.64794	0.37034
Wilks' Lambda		0.50060**	0.86285 (n.s.)
Coefficients	Cu	-0.49502	
	Pb	0.11292	
	Zn	0.90649	
	Ag	-0.06046	
	Au	0.29998	
Deposits of Paleozoic age and volcanic environment only (Fig. 9)			
Eigenvalue		2.68836	1.47310
% of variation explained		64.6	35.4
Canonical correlation		0.85374	0.77178
Wilks' Lambda		0.10963**	0.40435**
Coefficients	Cu	-0.84051	-0.30785
	Pb	0.99684	1.03445
	Zn	0.57014	-0.14570
	Ag	0.10093	-1.60387
	Au	-0.21442	-0.14288

* significant at 5% level; ** significant at 1% level; (n.s.) not significant.

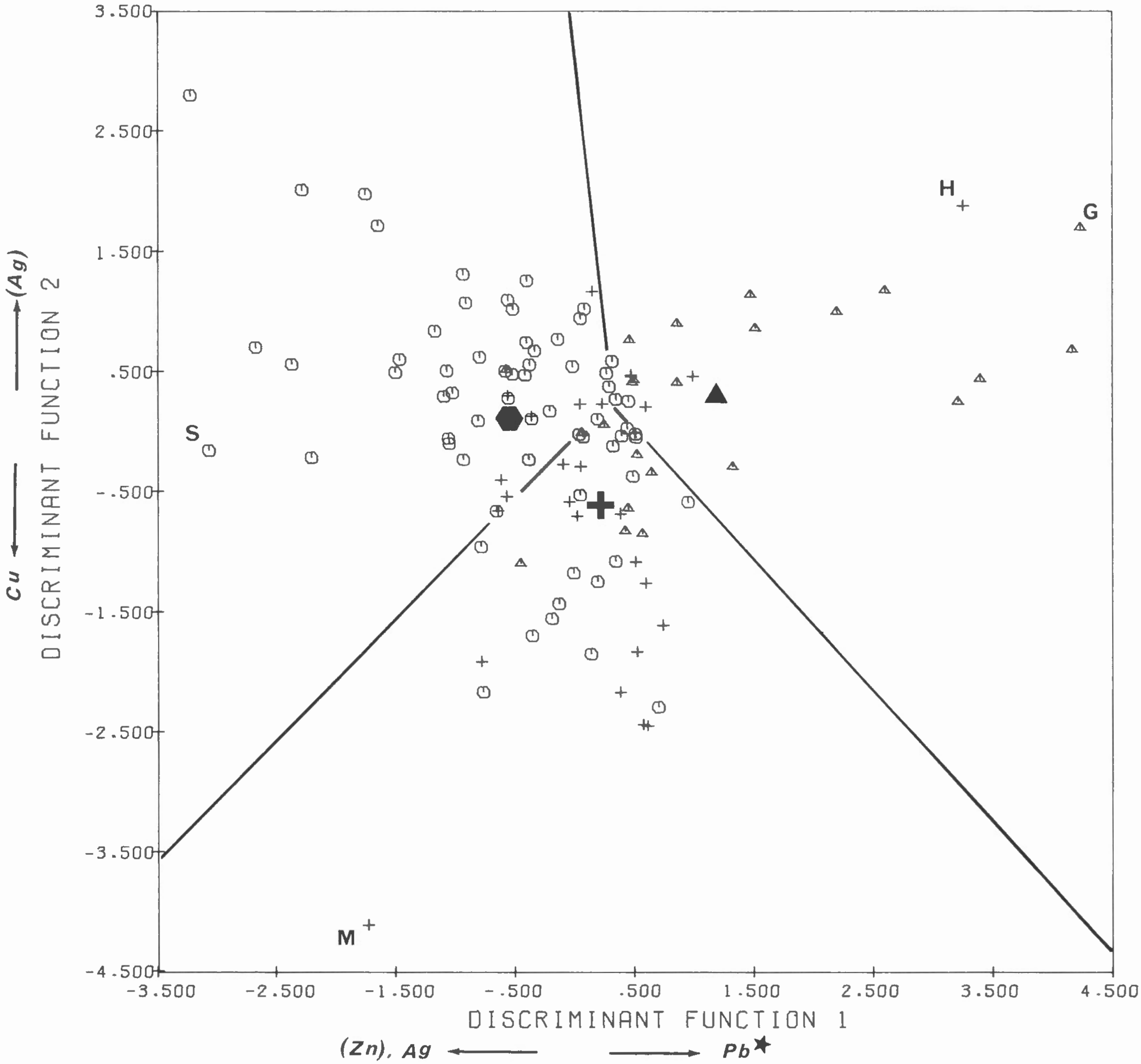

Figure 3. *Plot of discriminant scores for 118 deposits that occur in a volcanic environment, and subdivided into three age groups as in Figure 2. Symbols as in Figure 2.*

Although the group centroids are well separated from each other, a number of deposits in each group are misclassified. Again, as a result of possible continuous gradation in environmental character from predominantly sedimentary to predominantly volcanic, misclassification is more likely to the next group than to the farthest group (Table 2). The high percentage of misclassifications in the mixed group appears to reflect the highly variable ore composition of this group. It is possible that these deposits, in spite of the fact that they lie in a "mixed" environment, have had their metals derived from one or the other of the associated volcanic or sedimentary rocks, and should thus ideally be placed in one of these groups. In fact the presently accepted genetic models for these deposits (Sangster, 1972b; Sangster and Scott, 1976; Solomon, 1976; Hodgson and Lydon, 1977) would suggest that the metals could well be derived from rocks of the stratigraphic footwall, and that formation of the ore deposits should be completely independent of rocks forming the stratigraphic hangingwall. A further consideration is that the metals may well have been derived from as much as 700-2000 m into the stratigraphic footwall, whereas only a distance of up to 100 m is considered in this study. Also, some particular lithology from within the footwall stratigraphic sequence could have been the main metal source, but at present the criteria by which such a genetic affiliation can be established are only rarely adequate. Deposits that sit above a "feeder" alteration pipe with stringer mineralization may have had their metals derived from the underlying rocks. However, one would anticipate that the metals for deposits that have formed in more distal positions, i.e. farther from their feeder vents, are not derived from their immediate footwall rocks.

To remove the 'effect of age' on the deposits, the environment parameter has been tested for the 61 deposits of Paleozoic age only (Fig. 7). The results are similar to those when age differences were not considered.

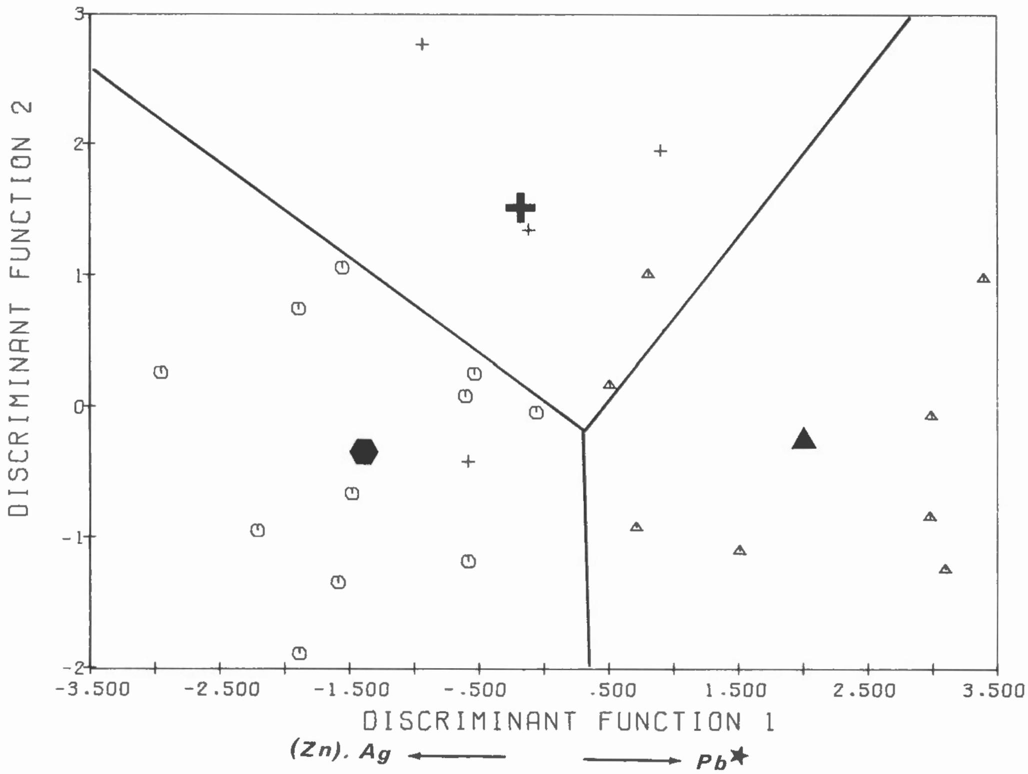

Figure 4. Plot of discriminant scores for 23 deposits that occur in a volcanic environment, and are associated with felsic volcanic rocks. Subdivision into three age groups and symbols as in Figure 2.

Volcanic Lithology Parameter

The standardized coefficients for the first discriminant function (Table 3) indicate that deposits with associated mafic volcanic rocks are essentially low in lead relative to copper and silver (for example, the Birch Lake deposit, L (Fig. 6), in the Flin Flon camp, contains 6.1% Cu). In contrast, the felsic volcanic group of deposits are richer in lead, and to a lesser extent in zinc relative to copper (for example, the Buchans deposit, B, contains 7.6% Pb and 14.6% Zn). These trends reflect group differences in mean grades for individual metals as shown in Table 1.

The second discriminant function separates copper (and possibly lead)-rich deposits that occur in the mafic volcanic environment from silver (and possibly zinc)-rich deposits belonging to the mixed lithology group. From examination of Table 1, deposits in the mafic environment are rich in copper relative to lead, thus diminishing the effect of the latter in the function. Similarly deposits in the mixed lithology group are rich in silver and zinc, relative to copper. The mixed deposits are also low in lead. For example, the Frebert (Abcourt) deposit (F) with 3.36 oz/ton silver is correctly classified in the mixed-volcanic group.

The pattern of misclassification of deposits is similar to that discussed previously. In two cases, however, apparent misclassification could be corrected where additional detailed knowledge improved the data. The first case is the Horne Mine (H) in the Noranda camp which contains 2.17% Cu but very low zinc and silver, and which is misclassified into the mafic group. If this deposit were combined with the zinc-bearing No. 5 zone (immediately adjacent to the Horne) a correct classification to the "mixed" group would result. In the second case, the copper-poor (0.2%) and zinc-rich (7.12%) Orvan Brook deposit (O) in the Bathurst camp is misclassified into the felsic volcanic group. The geology coded for this deposit was rechecked and it was found that a felsic classification would be more appropriate (Tupper, 1969).

As in the case of the environment parameter, the discriminant results were tested for independence from age changes by analyzing only the 51 Paleozoic deposits. Proper classification of the deposits into their respective groups improved relative to the test of the total population of deposits. Though the sample is small, the results show that grade characteristics are distinctly different for the three groups, and that the group centroids are properly separated on the only significant first discriminant function which accounts for 82 per cent of the variation (Fig. 8). This test again indicates that the mafic volcanic group of deposits is richer in copper, and deposits associated with felsic volcanic rocks are richer in lead and zinc.

It is interesting to note that of the 10 deposits in the mafic group, the one apparently misclassified deposit is Orvan Brook; it definitely occurs in felsic rocks (as noted previously) and consequently is incorrectly classified. Misclassification into volcanic lithology groups may be due to the erroneous assumption that the deposits are genetically related to their immediately adjacent rocks. Inherent in our model is the assumption that the metals are derived from the immediately adjacent strata. For example, in suggesting from our data that most copper-rich (lead- and zinc-poor) deposits are correlated with mafic rock hosts, we are inferring some grade-controlling genetic relation between rocks and ore. Misclassification may result, however, where the "parent" rock is not one of the immediately adjacent strata, or where a mixture of "parents" controlled the composition of the ore-forming solution. For example, the metals in deposits with both felsic and mafic volcanic rocks associated, may have been derived from rocks of both "parent" lithologies, yielding a unique (mixed lithology) group to which 60 per cent of the deposits in this study are assigned by discriminant analysis, or they may have been derived from either "end-member", and thus be incorrectly assigned (on the basis of genesis) to the "mixed" lithology group. As noted previously, there are only rarely satisfactory criteria for establishing specific metal sources.

A significant number of the deposits in our volcanic lithology data set contains appreciable (to a maximum of about 80%) sedimentary rocks in their immediate vicinity and belongs to the mixed environment group. For these deposits the influence of associated sedimentary rocks on ore composition may override any effect due to the composition of the associated volcanic rocks. To remove, as much as possible, any such influence due to the presence of sedimentary rocks and to remove as before the effect of age, discriminant analysis has been performed on the 24 Paleozoic deposits that occur in essentially volcanic environments (i.e. out of the 51 deposits used in Fig. 8, the 27 deposits occurring in environments containing significant sedimentary strata are eliminated). Correct classification improved to nearly 92 per cent and only two deposits belonging to the mixed (felsic-mafic) volcanic lithology group are misclassified, one into each of the adjacent groups (Fig. 9).

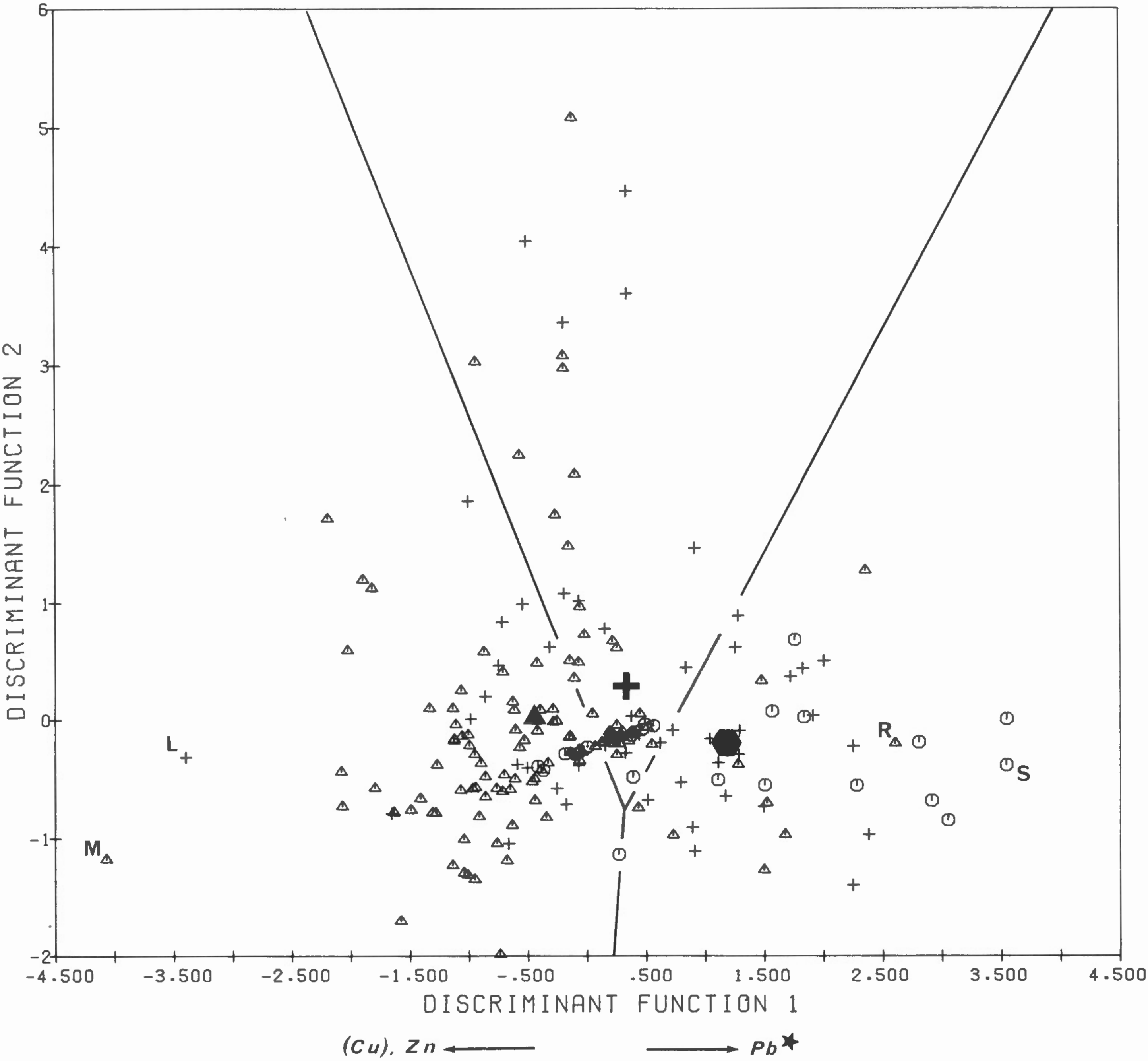

Figure 5. *Plot of discriminant scores for 201 deposits subdivided into three environmental groups. △ Deposits in a predominantly volcanic environment; ✚ Deposits in a mixed volcanic-sedimentary environment; ⬡ Deposits in a predominantly sedimentary environment. Letters (L, M, ...etc) represent deposits which are described in the text.*

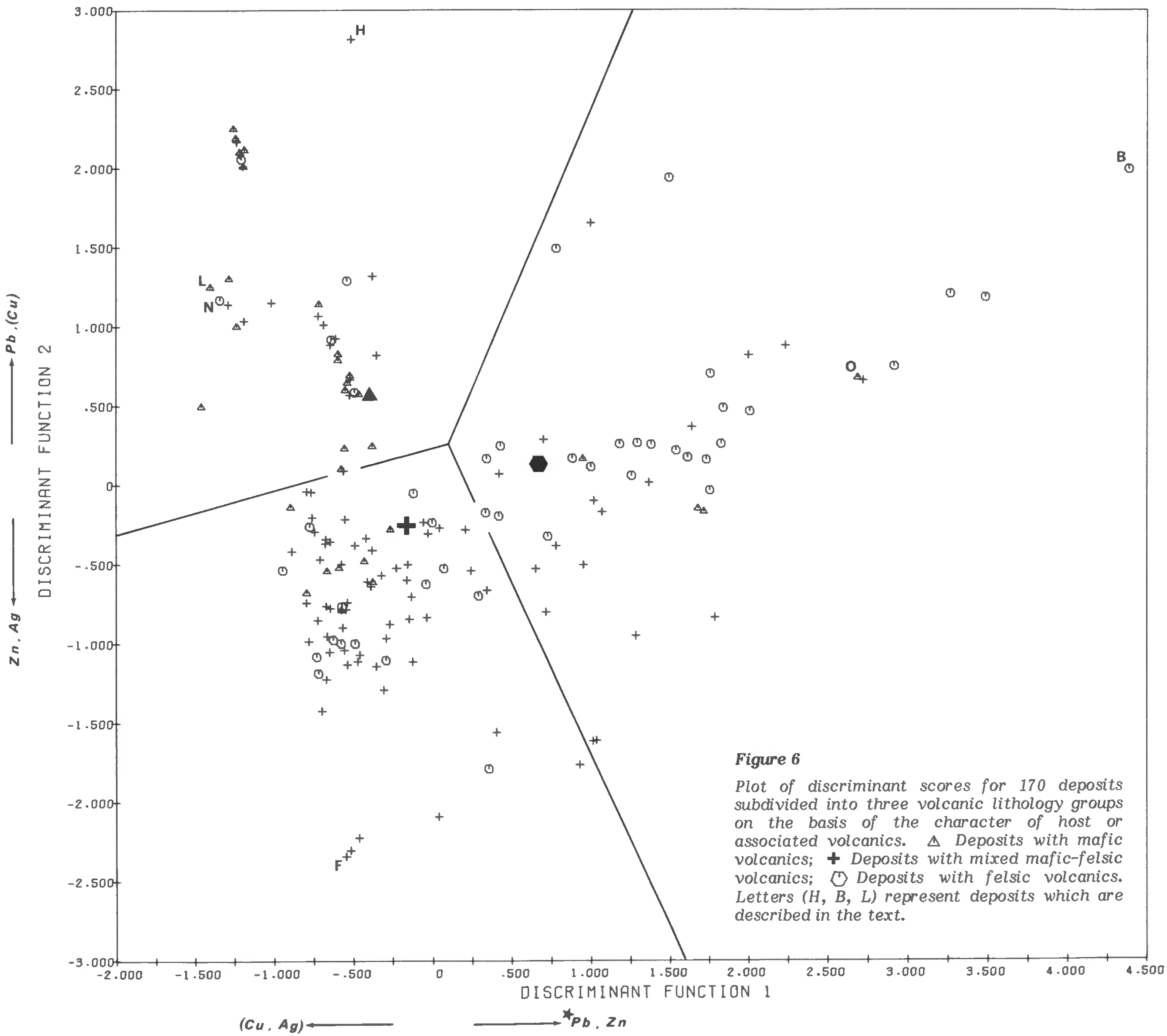

Figure 6

Plot of discriminant scores for 170 deposits subdivided into three volcanic lithology groups on the basis of the character of host or associated volcanics. △ Deposits with mafic volcanics; ✚ Deposits with mixed mafic-felsic volcanics; ⬡ Deposits with felsic volcanics. Letters (H, B, L) represent deposits which are described in the text.

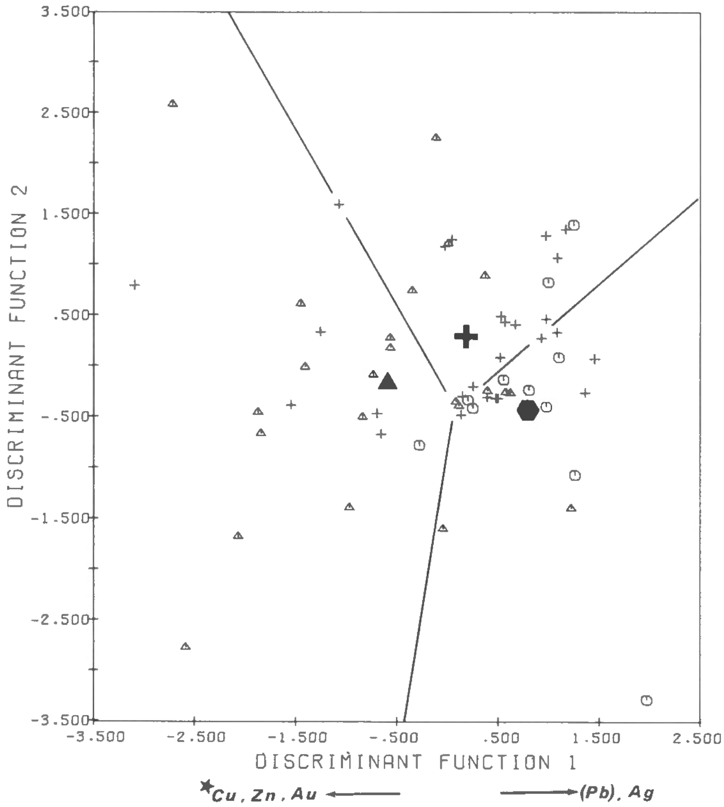

Figure 7. Plot of discriminant scores for 61 Paleozoic deposits subdivided into three environmental groups. Symbols as for Figure 5.

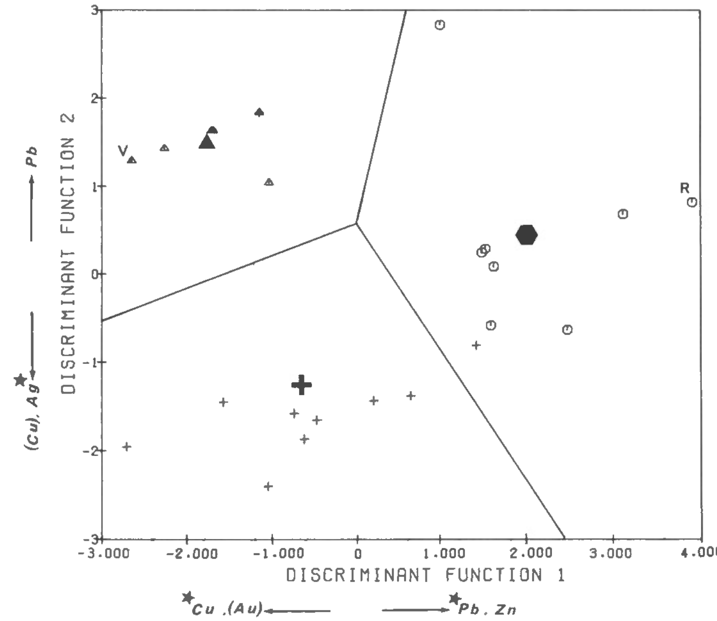

Figure 9. Plot of discriminant scores for 24 Paleozoic deposits that occur in a predominantly volcanic environment. The volcanic lithology groups and symbols are the same as in Figure 6.

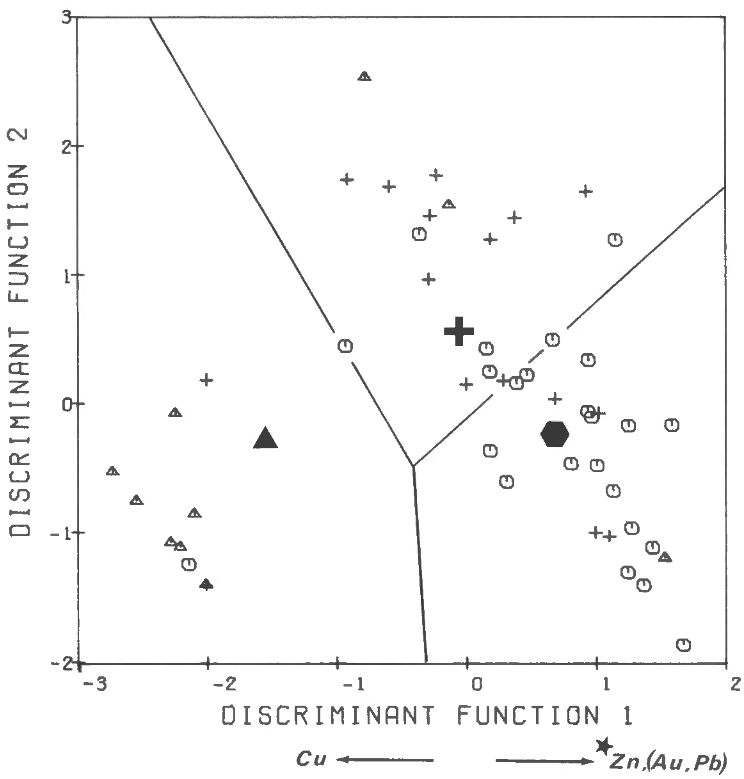

Figure 8. Plot of discriminant scores for 51 Paleozoic deposits subdivided into the same three volcanic lithology groups as in Figure 6. Symbols as in Figure 6.

Table 4

Contingency table indicating frequency of occurrence of deposits in each of different combinations of age- and environment-groups.

AGE	ENVIRONMENT		
	Volc.	Mixed	Sed.
Paleozoic	24	26	11
Proterozoic	28	9	7
Archean	66	16	1

DISCUSSION AND CONCLUSIONS

Discriminant analysis indicates that multivariate grade characteristics change 'continuously' with change of each of the three parameters, age, general geological environment and lithology of the associated volcanic rocks. For each parameter Canadian stratiform massive sulphide deposits have been divided into three groups which span the total age or lithological range and can be tested for differences in mean characteristics. In the case of the age parameter, this division is more objective and precisely defined as the deposits are clustered into three age groups, each separated by a distinct age gap. This may be the reason why discrimination was better for the age parameter than for the other two, where the divisions are more subjective and less precisely measured. Less distinct discrimination in the case of the environment and volcanic rock parameters may result in part from the subjective assignment of poorly documented deposits to specific classes. Another difficulty is that the influence of the environment parameter on the compositions of the deposits cannot be studied completely independently of the effect of the volcanic lithology parameter, and vice versa. Thus the effects of different volcanic lithologies within a single (volcanic environment) factor may be greater than the effect of volcanic versus sedimentary association. Similarly the amount of associated sedimentary rocks, and their compositional influence on the ores, is unaccounted for when the volcanic lithology parameter is studied.

Age Parameter

Discriminant analysis on the basis of deposit age indicated a relative decrease in lead and increase in zinc and silver grades as age increases. Archean deposits, as exemplified by Kidd Creek, Ontario and Mattagami Lake, Quebec, contain essentially zinc and copper, and, as widely recognized (Sangster, 1972b; Hutchinson, 1973; Solomon, 1976), are usually low in lead. In general, the Paleozoic deposits are polymetallic lead-zinc-copper type, represented at the Bathurst camp in New Brunswick and Buchans in Newfoundland, and reflect geological environments in which sedimentary rocks and/or felsic volcanic rocks form a very significant proportion of the lithologic succession.

The relationship we find between age and ore composition is no doubt overemphasized by the fact that many Paleozoic copper-zinc deposits in Newfoundland, such as Terra Nova and Betts Cove, and in the eastern Townships, Quebec, could not be included in the study due to the lack of reliable grade data. These deposits are associated with mafic volcanic rocks and ophiolitic sequences, similar to the deposits of Cyprus. Inclusion of these deposits would support the correlation of ore composition with volcanic lithology, but would probably weaken the correlation of ore composition with age.

Environment Parameter

Deposits of the volcanic-hosted group are richer in copper whereas deposits that are located in sedimentary environments are richer in lead. This relationship is independent of age-related compositional changes in ore deposits, as confirmed by investigating Paleozoic deposits alone. Possible explanations for this result are similar to those relating ore composition to the lithology of associated volcanic rocks, and are noted below.

Volcanic Lithology Parameter

Deposits associated with mafic volcanic rocks are richer in copper (and commonly gold), and those deposits in or associated with felsic volcanic rocks are richer in lead and zinc. Although some of Hutchinson's classifications and age assignments could be questioned, the general relationships between lithology and ore grades that he proposed are borne out by the present study using discriminant analysis. Support for such metal grade trends as a function of the composition of associated volcanic rocks comes from studies using rare earth elements as tracers of hydrothermal activity associated with the formation of massive sulphide deposits in volcanic rocks (Graf, 1977).

The possibility that ore grades are not dependent on volcanic lithology, but only on age was eliminated by again using a 51-deposit Paleozoic data set. Additionally, results presented in Figure 7 confirm the above relations between volcanic lithology and metal grades.

Speculation on the Causes of Observed Relationships

The low lead contents in Archean and Proterozoic deposits can be explained in a number of ways. Lead is slightly more abundant in younger sequences due to its accumulation as a product of radioactive decay of uranium and thorium but only approximately 6 per cent of the lead in the earth's crust has been added in the last 2.75 Ga, so the addition of radiogenic lead through geologic time may be only a partial explanation for the higher lead grades of younger deposits. Lead is enriched in crustal materials as a result also of geochemical evolution of the earth's lithosphere, hydrosphere and even atmosphere (Sangster and Scott, 1976, p. 213-214). Lead is generally more concentrated in potash-rich rocks, carbonate sequences, and manganiferous sedimentary rocks (Sangster, 1974). The potash content of Proterozoic and Paleozoic sequences is higher than that of Archean sequences, possibly due to its "fractionation" into the crust by crustal recycling and sedimentary accumulation. The higher grades of lead in deposits associated with sedimentary rather than volcanic environments, and in deposits with associated felsic rather than mafic volcanic rocks may thus reflect the lithologic distribution of lead. For example, lead grades are relatively high in certain Archean deposits, such as Sturgeon Lake (Franklin et al., 1975) and Hackett River, Northwest Territories, in which the footwall strata are rich in carbonate.

The variation in lead grade also may be controlled by the characteristics of the hydrothermal brines which transported the metals to their site of deposition. The metal contents and metal ratios of the brines are in part a function of brine temperature, and of the amounts and species of anions these brines contain. Such brines, if generated within the footwall sequences to massive sulphide deposits, will be compositionally controlled by the mineralogy and temperature of the reservoir in which they are generated (Lydon, 1978). As Lydon pointed out, provided that the solutions are saturated with metal, there is no basis for directly correlating the distributions of the ore metals in the reservoir rock and the brines generated within them. However, Lydon (1978) suggested that, in general, ore deposits that fall in a Zn-Cu compositional group probably formed in a high temperature, feldspar-mica buffered hydrothermal reservoir, and deposits that fall in a Zn-Pb compositional group in a lower temperature, clay-buffered reservoir. The former system could be reasonably associated with volcanic regimes, typified by high temperatures and mineralogy associated with igneous rocks (feldspar, mica) whereas the latter system would typify a lower temperature regime associated with clay-bearing sedimentary strata. A more thorough examination of the relationship between brines and reservoir rocks should be undertaken or further consideration should be given to the possibility that, contrary to one of the assumptions of Lydon (1978), the metal-transporting brines were undersaturated with regard to metals. Undersaturated brines might more closely reflect the metal content of the source or reservoir strata.

Within the precipitation environment (at or immediately below the seafloor surface) a variety of factors may have controlled the rate of deposition and relative abundance of each sulphide species including ore lead grade. For example, the relative difference in temperature (and density) of brines and overlying seawater (Sato, 1972) and possibly the availability of reduced sulphur, may control the rate of precipitation of each sulphide species. Fractional precipitation in the formation of the most lead-rich deposits cannot be ruled out as a possibility. Large (1977) has suggested that copper and then zinc may be precipitated from a brine with a high initial ratio of reduced to oxidized sulphur, as the temperature declines, possibly because of mixing with seawater, and as the proportion of reduced sulphur consequently decreases. The ores enriched in sulphates (and lead) may have formed under more oxidizing conditions, possibly explained by atmospheric evolution, with their zoning adequately accounted for by dropping temperature or increasing pH (Large, 1977). However, the suggested connection between ore composition and evolution of the atmosphere must be considered very dubious in the light of the lead- and barite-rich Big Stubby deposit (Sangster and Brook, 1977) which has an age of about 3450 Ma (Pidgeon, 1978).

Summary

The views of Hutchinson (1973), Sangster and Scott (1976), and Solomon (1976) regarding the general variations in grade characteristics with age, environment and volcanic-host composition of stratiform massive sulphide deposits, have been given an objective, statistical test and been found to be statistically supported. This support, arising from the discriminant analysis procedure used, ranges in strength from weak to at least moderate.

Of the five metal grades, copper, lead, zinc, silver and gold, that were analyzed in the present study, the most significant in indicating specific trends are lead and copper. Lead grade increases relative to other metals in younger deposits possibly due to the increase in the sedimentary character of their environments, or with a more felsic nature to their volcanic host rocks. In contrast relative copper grade increases in deposits that occur in volcanic environments (i.e. close to volcanic centres) and with a more mafic nature to the volcanic host rocks.

The present study has confirmed the empirical correlations between ore grades and age, lithologic association and volcanic composition. These correlations could, through appropriate statistical procedures, be used in mineral resource appraisals to predict the grades and metal ratios of prognosticated deposits. The desirability and mechanics of incorporating these parameters into regional resource potential estimates could form the subject of a future study.

Further investigation of the causes for the statistical misclassifications would be useful. Some may be due to faulty data, e.g. incorrect lithological determinations or inclusion of only part of an orebody in the grade data. Some may be due to factors that cannot be taken account of because data are insufficient, e.g. temperatures of ore-depositing solutions; some may be due to totally unrecognized factors. Deposits whose compositions are unrelated to host-rock lithology, as might be the case for deposits formed at a considerable distance from their exhalative centre or source rock, could be "misclassified" in the present study. Statistical misclassification of a deposit serves as a "flag" to indicate the need for re-appraisal of the information on it and may lead to a better understanding of its genesis.

In the present study, the classification was highly successful (e.g. 92%) when based on groups defined by specific geological criteria but success was low (e.g. 53%) when definitions of groups were less rigorous. We anticipate that relationships between the compositions of deposits and their lithological and environmental characteristics can be defined more successfully as data improve; the classifications will then be based on more homogeneous groups, i.e. all deposits in a given group will have closely similar geological characteristics. For example, assuming a volcanic-exhalative genetic model, the classification should improve if the lithology of the stratigraphic footwall only (instead of "enclosing rocks") is considered. Although the number of deposits in the study would be reduced, by eliminating those whose stratigraphic footwall is not positively identified, the possibilities for improvement of classification are attractive. Further refinements of our procedure might include use of minor and trace element data, more precise definition of lithology, and widening of the data base by including foreign deposits.

The present study confirms empirical correlations between ore grades and age, lithologic association, and volcanic composition. These correlations could, through appropriate statistical procedures, be used in mineral resource appraisals to predict the grades and metal ratios of prognosticated deposits. With further improvements such as we have suggested, the method could provide a useful input to estimation of regional mineral resources.

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APPENDIX 1

201 stratiform massive sulphide deposits in Canada

Name	Latitude ° ' "	Longitude ° ' "	Age (Ma)	Environment	Volcanic Lithology	Cu (%)	Pb (%)	Zn (%)	Ag (oz/ton)	Au (oz/ton)
Amulet A & Lower A	48 19	79 5	2800	Volcanic	Mixed	5.12	—	5.47	1.36	.043
Amulet C	48 19	79 5	2800	Volcanic	Mixed	2.20	—	8.50	2.53	.017
Amulet F	48 20	79 3	2800	Volcanic	Mixed	3.54	—	3.40	.14	.015
Anaconda Caribou	47 33 50	66 17 56	445	Mixed	Felsic	.47	1.70	4.48	1.71	.048
Anderson Lake	54 51	100 0 30	1800	Volcanic	Mixed	3.79	—	—	.21	.013
Armstrong A	47 34	66 17 30	445	Volcanic	Felsic	.29	.42	2.29	.07	.020
Armstrong B	47 36	66 3	445	Volcanic	Felsic	.20	.15	1.50	.05	.020
Austin Brook	47 24	65 48	445	Mixed	Felsic	.10	1.86	2.93	1.00	—
Barvallee Mine	48 26	77 42	2800	Mixed	Felsic	1.23	—	5.71	1.42	—
Barvue Mine	48 31 18	77 40 30	2800	Volcanic	Mixed	—	—	3.50	1.30	—
Belfort (Roymont)	48 25 55	77 40 55	2800	Volcanic	Mixed	.21	.12	7.00	.61	—
Bell Allard	49 41	77 44	2800	Volcanic	Felsic	.96	—	8.15	.53	.005
Bell Allard (Radiore 2)	49 45	77 35	2800	Volcanic	Felsic	2.00	—	1.00	—	—
Bell Channel No. 1	49 46	77 37	2800	Volcanic	Mixed	1.95	—	.57	—	—
Big Bull	58 38 24	133 35 24	200	Volcanic	Mixed	1.32	1.31	6.06	3.30	.092
Big Nama Creek	49 11	85 50	2800	Mixed		.83	—	4.16	1.04	—
Birch Lake	54 2 30	102 2 15	1800	Volcanic	Mafic	6.17	—	—	.12	.003
Bob Lake	55 9 30	101 2 45	1800	Sediment.		1.33	—	1.80	.27	.010
Bomber Deposit	54 51 40	100 10 58	1800	Volcanic	Felsic	.04	—	1.00	.25	.003
Boot Lake (Hackett R.)	65 54 14	108 25 26	2800	Mixed	Mixed	—	1.00	5.00	5.86	—
Brabant (McKenzie)	56 8	103 40	1800	Sediment.		.64	—	4.43	.14	.002
Britannia	49 36 36	123 8 30	150	Mixed	Mafic	1.07	—	.28	.15	—
Brunswick 12	47 28 30	65 53 40	445	Mixed	Mixed	.30	3.74	9.12	2.73	—
Brunswick 12 (Cu)	47 28 30	65 53 40	445	Mixed	Mixed	1.11	.45	1.27	1.03	—
Brunswick 6	47 24 36	65 49 17	445	Mixed	Felsic	.36	2.19	5.59	2.03	—
Buchans	48 49	56 53	430	Volcanic	Felsic	1.33	7.64	14.64	3.56	.047
Calumet Mine	45 42	76 41	1300	Mixed	Mafic	.12	1.66	5.95	3.54	.019
Canoe Landing	47 24 30	66 6	445	Sediment.		.50	.50	1.50	1.47	.040
Can. Jamieson	48 30 55	81 34 7	2800	Volcanic	Mixed	2.26	—	3.29	.80	.008
Captain Deposit	47 17	65 52 38	445	Mixed	Mafic	1.99	—	—	.28	.017
Centennial	54 42 3	101 39 59	1800	Volcanic	Mafic	2.06	—	2.60	.70	.040
Chester Diss.	47 7	66 14 20	445	Sediment.		1.26	—	—	—	—
Chester	47 7	66 14 20	445	Mixed	Felsic	.77	.83	2.12	1.20	.040
Chester Pb-Zn	47 7	66 14	445	Mixed	Felsic	.63	.83	2.12	—	—
Chisel Lake	54 49 43	100 7	1800	Volcanic	Mixed	.56	.82	11.61	1.25	.048
Clinton Copper	45 27 36	70 54 30	390	Volcanic	Mixed	1.99	.05	1.39	.38	—
Colchester + 3 others	49 38 15	54 4 55	500	Volcanic	Mafic	1.39	—	—	—	—
Coniagas Mine	49 29 54	76 9 48	2800	Volcanic	Mixed	—	.87	9.10	4.59	—
Cons. Mogador	48 26	77 40	2800	Volcanic	Felsic	.47	.34	7.30	1.62	.034
Cons. Northern Expl.	49 26	78 17	2800	Volcanic	Mixed	.73	—	6.95	1.00	—
Cons. Pershcourt	48 31	77 42	2800	Volcanic	Mixed	—	—	2.42	2.43	—
Cons. Rambler-Main	49 53 33	56 5	500	Volcanic	Mixed	1.29	—	2.20	.82	.151
Cons. Rambler-Ming	49 54 50	56 4 50	500	Volcanic	Mixed	2.83	—	—	.49	.058
Copper Man	54 39 12	99 52 5	1800	Volcanic	Mafic	2.63	—	4.46	—	—
Copper-Lode E	50 58	92 52 40	2800	Volcanic	Mixed	.66	—	4.80	.39	—
Copper-Lode Main	50 58 45	92 57 30	2800	Mixed	Mafic	1.56	—	—	.98	—
Corbet Lake	48 18	79 4 55	2800	Volcanic	Mixed	3.68	—	2.14	.74	.037
Coronation Mine	54 35	101 59 30	1800	Volcanic	Mafic	4.26	—	.15	.15	.060
Creek Zone (Mattagami)	49 52 54	90 5	2800	Volcanic	Mixed	1.66	.88	8.16	4.19	.013

Appendix 1 (cont.)

Name	Latitude ° ' "	Longitude ° ' "	Age (Ma)	Environment	Volcanic Lithology	Cu (%)	Pb (%)	Zn (%)	Ag (oz/ton)	Au (oz/ton)
Cupra Mine	45 46	71 19	500	Volcanic	Mixed	2.69	.37	3.11	1.03	.013
Cuprus	54 43 45	101 42 13	1800	Mixed	Mafic	3.24	—	6.40	.84	.040
Delbridge Mine	48 16	78 55	2800	Volcanic	Mixed	.49	—	9.40	2.80	.080
Detour (Selco) A1 Zone	49 49	78 55 58	2800	Volcanic		.39	—	2.30	1.04	.009
Detour (Selco) A2 Zone	49 49	78 55 55	2800	Volcanic		2.26	—	1.24	.049	.023
Detour (Selco) B Zone	49 49 4	78 56 16	2800	Volcanic		4.49	—	.80	1.15	.036
Devils Elbow	47 25 51	66 23 57	445	Mixed	Felsic	1.05	—	—	—	—
DH-FL Groups	56 49	101 1	1800	Mixed	Mafic	.90	—	2.20	—	—
Dickstone	54 51 10	100 29	1800	Volcanic	Mafic	2.58	—	3.29	.40	.014
Don Jon Mine	54 46	101 35	1800	Volcanic	Mixed	3.09	—	—	.44	.027
D'Eldona Gold	48 15 54	78 57 53	2800	Volcanic	Felsic	—	—	7.70	2.00	.170
D'Estrie	45 46	71 19	500	Volcanic	Mixed	2.87	.64	2.15	1.16	.016
East Cleaver L.	65 54 14	108 26 27	2800	Mixed	Mixed	.50	1.00	7.00	5.30	.014
East Sullivan	48 5	77 42	2800	Mixed		.96	—	.47	.21	.007
East Waite	48 21	79 2	2800	Volcanic	Mixed	4.13	—	3.26	.91	.053
Empire Oil (Le Tac)	49 26 49	76 9 30	2800	Volcanic	Mixed	.23	—	2.45	.15	—
Errington-Vermilion	46 32	81 16 28	1850	Mixed	Felsic	1.19	.98	3.85	1.59	.028
Faro/Anvil	62 21 30	133 22	160	Sediment.		—	3.90	5.22	1.00	—
Flexar Mine	54 40 45	102 2	1800	Volcanic	Mafic	3.77	—	.47	.19	.040
Flin Flon	54 45 28	101 53	1800	Volcanic	Mixed	2.31	—	4.25	1.25	.082
Fox Lake Mine	56 38	101 37	1800	Mixed	Mafic	2.06	—	1.96	.03	.010
Frebert (Abcourt)	48 31	77 43	2800	Volcanic	Mixed	—	—	1.95	3.36	—
Frotet Lake (Lessard)	50 45	74 40	2800	Volcanic	Felsic	1.73	—	2.96	1.10	.019
Garon Lake	49 46	77 35	2800	Volcanic	Mixed	1.58	—	2.17	.12	.004
Geco Mine	49 9	85 47	2800	Mixed		1.88	—	3.49	1.48	—
Ghost Lake	54 49 10	100 4	1800	Volcanic	Mixed	1.88	.32	12.05	1.29	.033
Goldstream River	51 37	118 13	550	Mixed	Mafic	4.49	—	3.24	.62	—
Grandora (Shunsby)	47 42 48	82 39 30	2800	Mixed	Mafic	1.20	—	1.28	—	—
Grum	62 16 10	133 13 20	160	Sediment.		—	4.23	6.69	1.88	—
Gullbridge	49 11 49	56 9 18	445	Volcanic	Mixed	.80	—	—	—	—
Hackett River A	65 55 05	108 22	2800	Mixed	Mafic	.25	1.50	8.50	7.00	.050
Half Mile Lake (Keevil)	47 17	66 19	445	Mixed	Mixed	.44	.79	6.01	.05	—
Hanson Lake	54 40 30	102 51	1800	Volcanic	Felsic	.51	5.83	9.99	4.00	—
Hart River	64 38 10	136 49	1100	Sediment.	Mafic	1.45	.87	3.65	1.45	.041
Heath Steele	47 18	66 3	445	Volcanic	Felsic	1.15	1.67	4.55	1.74	—
High Lake AB Zone	67 23	110 51 40	2800	Volcanic	Mixed	5.40	—	1.10	—	.030
High Lake D Zone	67 22 30	110 51 20	2800	Volcanic	Mixed	2.00	.20	3.60	1.10	.020
Hood River No. 10	66 4	112 45	2800	Volcanic	Mixed	4.77	—	3.62	.77	—
Horne Mine	48 15 16	79 0 41	2800	Volcanic	Mixed	2.18	—	—	—	.150
Hudvam (Vamp Lake)	54 56 30	101 10 15	1800	Volcanic	Mafic	1.50	—	1.70	.43	.010
Huntingdon Mine (Sullivan)	45 15 50	72 19 45	500	Mixed	Mafic	.93	—	—	.024	.002
Indian Mountain Lake	63 2 45	110 56 55	2800	Mixed	Mixed	.20	.85	10.30	2.45	—
Iso-Copperfields Cu	48 26 30	79 23	2800	Volcanic	Mixed	2.10	—	.32	1.00	.007
Iso-Copperfields Zn	48 26 30	79 23	2800	Volcanic	Mixed	.40	—	5.50	.78	.046
Ives Mine	45 17 20	72 19 25	500	Volcanic	Mafic	3.50	—	—	—	—
Izok Lake	65 37 45	112 47 30	2800	Volcanic	Mixed	3.15	1.20	14.80	1.85	—
Jameland Mine	48 34	81 34	2800	Volcanic	Mixed	.99	—	.88	.083	.001
Joannie	54 49	100 0	1800	Volcanic	Mixed	1.28	—	—	—	—
Joutel Copper (Cu Zone)	49 28	78 23	2800	Volcanic	Mixed	2.16	—	—	—	—
Joutel Copper (Zn Zone)	49 28	78 23	2800	Volcanic	Mixed	—	—	8.90	—	—

Appendix 1 (cont.)

Name	Latitude ° ' "	Longitude ° ' "	Age (Ma)	Environment	Volcanic Lithology	Cu (%)	Pb (%)	Zn (%)	Ag (oz/ton)	Au (oz/ton)
Jungle Lake	54 31 45	100 58	1800	Sediment.		1.42	—	1.00	—	—
Kam Kotia	48 36 9	81 36 45	2800	Volcanic	Mixed	1.12	—	1.22	.103	.001
Kendon Copper	50 25 25	87 36 30	2800	Sediment.	Felsic	1.45	—	4.76	—	—
Kennedy Lake	63 2 2	110 57 30	2800	Mixed	Mixed	—	1.00	6.00	5.00	—
Kidd Creek	48 41 30	81 22	2800	Mixed	Mixed	2.40	.24	6.93	2.92	—
Knobby Lake	56 52	99 59	1800	Volcanic	Mafic	.35	—	8.77	—	—
La Gauchetiere	49 46 29	78 9 19	2800	Volcanic		.90	—	4.50	.50	—
Lake Dufault No. 2	48 18	79 4	2800	Volcanic	Mixed	.50	—	9.80	3.00	.040
Lemoine (Patino)	49 45 44	74 6 10	2800	Mixed	Felsic	4.50	—	10.80	2.70	.138
Lingwick	45 39 27	71 23	500	Volcanic	Mixed	.60	—	6.00	.47	—
Little Bald Mtn. (Cu)	47 19 30	66 22 30	445	Mixed	Mixed	2.00	1.00	5.00	—	—
Little Bald Mtn. (Pb-Zn)	47 19 30	66 22 30	445	Mixed	Mixed	.32	2.69	6.97	.28	—
Little Bay Mine	49 36	55 56	500	Volcanic	Mafic	1.32	—	—	—	.002
Little Deer Pond	49 34 37	56 0 30	500	Volcanic	Mafic	2.40	—	—	—	—
Lost Lake	54 49 47	100 6 36	1800	Volcanic	Felsic	1.45	1.00	4.90	2.37	.085
Louvem (Zn Ore)	48 5 54	77 31 11	2800	Volcanic	Felsic	.21	—	6.29	.97	.036
Lynx (Obaska)	49 38 48	77 43 18	2800	Volcanic	Mixed	1.60	—	.35	—	—
Lyon Lake	49 53	90 52	2800	Volcanic	Mixed	1.00	.56	6.22	3.16	.009
MacMillan Pass	63 9 57	130 9	355	Sediment.		—	8.10	8.40	2.75	—
Mandy	54 43 45	101 50	1800	Volcanic	Mixed	7.30	—	12.90	1.80	.090
Manitou Barvue	48 5 12	77 36 36	2800	Volcanic	Mixed	.28	.22	2.71	1.90	.025
Manitou Barvue (2 Ore)	48 5 12	77 36 36	2800	Volcanic	Mixed	—	.32	2.19	5.92	—
Mattabi Mine	49 52 30	90 58 30	2800	Volcanic	Mixed	.82	.77	7.49	3.10	.010
Mattagami Lake	49 43	77 44	2800	Volcanic	Mixed	.65	—	8.40	.95	.015
McMaster	47 36 28	66 14 13	445	Sediment.		.60	—	—	—	—
Middle Landing	47 26 15	65 41 55	445	Sediment.		.24	2.18	5.87	2.30	—
Millenbach	48 18	79 3	2800	Volcanic	Mixed	3.43	—	4.23	1.38	.024
Mines de Poirier	49 26 24	78 23 24	2800	Volcanic	Mixed	1.51	—	.96	.049	—
Mobrun	48 24	78 54	2800	Volcanic	Mixed	.62	—	2.32	.62	.052
Montauban	46 50 30	72 21	1300	Mixed	Mixed	—	1.07	3.39	1.11	.015
Moulton Hill	45 25 35	71 48 48	500	Volcanic	Mixed	.81	1.86	2.34	2.27	.077
Murray Bk. Pyritic Ore	47 31 30	66 26	445	Sediment.		.26	.65	1.22	—	—
Murray Brook Pb-Zn	47 31 30	66 26	445	Sediment.		.16	2.08	5.55	2.08	.016
Murray Brook (Cu)	47 31 30	66 26	445	Sediment.		1.07	.48	1.04	—	—
Nepisiguit A	47 22	66 3	445	Mixed	Felsic	.40	.60	2.80	.30	—
Nepisiguit B	47 22	66 3	445	Mixed	Felsic	.10	.40	1.90	.30	—
Nepisiguit C	47 22	66 3	445	Mixed	Felsic	.40	.70	2.10	.60	—
New Bay Pond	49 16 36	55 37 58	445	Mixed	Mixed	.50	—	2.00	—	—
New Formaque (Conigo)	48 36	78 4	2800	Volcanic	Felsic	1.10	—	.31	.78	—
New Hosco	49 47	77 51 30	2800	Volcanic	Felsic	1.35	—	.99	.12	.001
New Insco	48 26 30	79 20 40	2800	Volcanic	Mixed	2.11	—	—	—	—
Nine Mile Brook	47 25	66 1	445	Mixed	Felsic	.42	1.23	1.00	2.65	.030
Norbec, Lake Dufault	48 21	79 4	2800	Volcanic	Mixed	2.78	—	4.76	1.03	.016
Norita (Radiore A)	49 46	77 41	2800	Volcanic	Mixed	.70	—	7.60	1.00	.018
Normetal	49 0	79 22	2800	Volcanic	Mixed	2.15	—	5.12	1.32	.016
North Star	54 46	101 35	1800	Volcanic	Felsic	6.10	—	—	.23	.010
No. 41 Deposit	66 4	112 45 0	2800	Volcanic	Mixed	1.57	—	4.12	.52	—
Orchan Mine	49 42	77 44	2800	Volcanic	Mixed	1.05	—	9.93	.60	.006
Orvan Brook West	47 38	66 8	445	Mixed	Mafic	.20	3.27	7.12	2.50	.017
Orvan Brook (New Calumet)	47 37	66 7	445	Sediment.	Felsic	.30	2.20	4.10	2.00	.017
Osborne Lake	54 57 15	99 43 24	1800	Sediment.		3.69	—	1.53	—	—

Appendix 1 (cont.)

Name	Latitude ° ' "	Longitude ° ' "	Age (Ma)	Environment	Volcanic Lithology	Cu (%)	Pb (%)	Zn (%)	Ag (oz/ton)	Au (oz/ton)
Pabineau River (Headway)	47 26 41	65 55	445	Volcanic	Felsic	1.43	2.10	6.16	.61	—
Panet Metals	46 35 15	70 13 10	445	Sediment.		.40	.43	2.67	.58	.060
Pinebay	54 45 50	101 37 3	1800	Volcanic	Mixed	1.30	—	—	—	—
Pot Lake	54 46 12	100 10 30	1800	Volcanic	Mafic	1.32	—	4.50	.55	.011
Potter Mine (Munro Cu)	48 29 27	80 11 50	2800	Volcanic	Mafic	2.05	—	1.67	—	—
Quemont	48 15	78 58	2800	Volcanic	Felsic	1.31	.018	2.43	.91	.157
Rail Lake	54 44 30	100 35 50	1800	Mixed		3.00	—	.70	—	—
Ramsay Showing	54 44 20	102 45 30	1800	Mixed		2.04	—	1.60	—	—
Reed Lake (Freeport)	54 34 26	100 19 33	1800	Volcanic	Mixed	2.00	—	4.00	—	—
Reed Lake (H.B.M.S.)	54 37 55	100 33 53	1800	Volcanic	Mixed	2.09	—	—	—	—
Restigouche Mining	47 29 40	66 32	445	Volcanic	Felsic	.31	4.60	5.90	2.50	.020
Rocky Turn	47 37 30	66 3	445	Volcanic	Felsic	.30	1.50	7.00	2.30	.050
Ruttan Lake	56 28	99 28	1800	Volcanic	Mixed	1.41	—	1.54	.20	.010
Schist Lake	54 43	101 49 50	1800	Volcanic	Mixed	4.33	—	7.17	1.05	.040
Schotts Lake	55 6	102 8	1800	Sediment.		1.00	—	—	—	—
Sherridon Mine	55 6 39	101 5	1800	Mixed	Mixed	2.37	—	2.28	.55	.020
Solbec Copper	45 49	71 18 30	500	Volcanic	Mixed	1.31	.44	3.53	.85	.014
Soucy No. 1 Zone A	58 19	69 53	1600	Mixed	Mafic	1.34	—	1.87	.54	.077
South Bay Mine	51 6 30	92 40 45	2800	Volcanic	Mixed	1.96	—	12.50	2.91	—
Stall Lake (H.B.M.S.)	54 51 36	99 56 14	1800	Volcanic	Mixed	4.76	—	.65	.31	.039
Stall Lake (Rod)	54 57 36	99 55 12	1800	Volcanic	Mixed	5.38	—	2.28	—	—
Stirling	45 44	60 26	570	Mixed	Felsic	.71	1.46	6.21	2.08	.030
Stratmat East (Cu)	47 19 13	66 6 31	445	Mixed	Felsic	2.20	.10	.30	—	—
Stratmat East (Pb-Zn)	47 19 13	66 6 31	445	Mixed	Felsic	.10	2.00	6.00	1.90	—
Stratmat West (Tomogon.)	47 18 32	66 8 3	445	Mixed	Felsic	.10	4.00	9.50	1.20	—
Sturgeon Lake (Boundary)	49 52 30	90 52	2800	Volcanic	Mixed	2.74	1.41	10.01	5.67	.020
Suffield Mine	45 19	71 57	500	Mixed	Felsic	.91	.52	7.00	2.65	.080
Sullivan Mine, B.C.	49 42 30	116 0 25	1370	Sediment.		—	5.80	5.50	1.84	—
Tache Lake	49 57	74 24	2800	Volcanic	Mixed	—	—	7.49	.82	.181
Teahan	45 43	64 59	750	Volcanic	Mixed	.46	—	1.46	.87	—
Tetreault	46 49 30	72 20	1300	Mixed	Mixed	—	1.56	4.53	2.50	.020
Tom Group	63 10 10	130 8 20	355	Sediment.		—	4.00	6.10	1.26	—
Trinity Property	48 42 30	77 45 35	2800	Mixed	Mixed	1.18	—	.74	—	—
Troilus Lake (Frotet L.)	50 51	74 34	2800	Volcanic	Felsic	1.92	—	5.87	1.21	—
Trout Bay Cu	51 0 32	94 12	2800	Mixed	Mixed	1.42	.24	7.56	1.62	.007
Tulk's Brook (Terra Nova)	48 31	57 12 30	445	Volcanic	Felsic	1.50	1.50	5.00	—	—
Vangorda Creek	62 15	133 9 45	160	Sediment.		.27	3.18	4.96	1.76	.020
Vauze Mine	48 22	79 4	2800	Volcanic	Mixed	2.90	—	.94	.70	.019
Waite Amulet	48 20	79 6	2800	Volcanic	Mixed	4.70	.038	2.97	.63	.032
Wedge Mine	47 23 50	66 8 30	445	Mixed	Felsic	2.87	.67	2.11	.50	.010
Weedon Mine	45 42	71 23	500	Volcanic	Mixed	3.35	—	.64	.155	.006
West Macdonald	48 20	78 57	2800	Volcanic	Felsic	.014	—	2.69	.055	—
Westarm	54 38 30	101 50 12	1800	Mixed	Mafic	4.63	—	.60	—	—
Western Mines	49 34 12	125 34 48	280	Volcanic	Felsic	1.41	1.03	7.44	3.10	.060
Whalesback Mine	49 35 30	56 0 30	500	Volcanic	Mafic	.80	—	—	—	—
White Lake	54 42 40	101 43 30	1800	Volcanic	Mixed	2.27	—	4.83	.95	.018
Wildnest Lake	55 3	102 2	1800	Sediment.		.61	—	1.20	—	—
Willroy + Willecho	49 9 30	85 49 34	2800	Mixed		.94	.18	4.62	1.74	—
Wim	55 1 31	100 2 38	1800	Sediment.		2.91	—	—	—	—
York Harbour	49 2 8	58 18 5	500	Volcanic	Mafic	2.70	—	8.75	—	—
Z Deposit	56 49 57	101 1 30	1800	Mixed	Mixed	1.11	—	2.49	—	.016

APPENDIX 2

Multiple discriminant analysis procedure

The Fisher's linear discriminant function for two groups can be obtained by maximizing the ratio of the sum of squares between groups to the sum of squares within groups for some linear combination (Anderson, 1958). This method can also be extended to the case of g (>2) groups (Kshirsagar, 1972). However, there would be g-1 linear discriminant functions, provided that the number m of variables is greater than or equal to g. Suppose that $v_1'x, v_2'x, \ldots, v_{g-1}'x$ represent the g-1 discriminant functions of sample x, where $v_1, v_2, \ldots, v_{g-1}$ are the corresponding vectors of coefficients. Then the coefficients can be obtained by maximizing the ratio

$$\frac{v'Bv}{v'Wv} \tag{1}$$

where B and W are the matrices of sum of squares between groups and sum of squares within groups, respectively, for some linear combination v'x.

To maximize the ratio in (1), we differentiate the equation (1) with respect to v and set it equal to zero, i.e.,

$$(v'Wv)Bv - (v'Bv)Wv = 0 \tag{2}$$

Dividing (2) by v'Wv, we have

$$Bv = \frac{v'Bv}{v'Wv} Wv \tag{3}$$

implying that

$$W^{-1}Bv = \lambda v \tag{4}$$

where $\lambda = \frac{v'Bv}{v'Wv}$ if W^{-1} exists. From (4), λ is obviously an eigenvalue of $W^{-1}B$ and v is the corresponding eigenvector. The rank of $W^{-1}B$ is g-1 when m > g-1. Thus, the g-1 orthogonal eigenvectors of $W^{-1}B$ are the coefficients of the discriminant functions. Without loss of generality, we may assume that

$$\lambda_1 > \lambda_2 > \ldots > \lambda_{g-1} \tag{5}$$

and $v_1, v_2, \ldots, v_{g-1}$ are the corresponding eigenvectors with $v_i'v_i = 1$ (i = 1,2,...,g-1). Hence, the first discriminant function $v_1'x$ of the largest eigenvalue λ_1 provides maximum separation of the groups. The relative ability of the i-th discriminant function $v_i'x$ in separating the groups is indicated by the associated canonical correlation coefficient ρ_i defined as

$$\rho_i = \frac{\lambda_i}{1 + \lambda_i} \quad (i = 1,2,\ldots, g-1) \tag{6}$$

As each successive discriminant function is derived, a Wilks' lambda is computed to test the statistical significance of discrimination afforded by the remaining functions. Suppose that we have i discriminant functions already, then the Wilks' lambda, Λ_i, is obtained by

$$\Lambda_i = \prod_{j=i+1}^{g-1} \frac{1}{1+\lambda_j} \quad (i = 0,1, \ldots, g-2) \tag{7}$$

Λ_i is an inverse measure of the discriminating power existing in the remaining functions. It is known (Cooley and Lohnes, 1971) that $-(n-1/2(m+g)-1)\log_e \Lambda_i$ has a χ^2 distribution with (m-i)(g-i-1) degrees of freedom.

Using the k discriminant functions that are found to be significant based on the above χ^2 statistics, samples are classified as follows. Initially, for each sample x_{ij} (whose group membership is known) i.e. j-th sample from i-th group, k discriminant scores $d_{ij1}, d_{ij2}, \ldots, d_{ijk}$ are computed for all $j=1,2,\ldots,n_i$ and $i=1,2,\ldots,g$. n_i is the number of samples in the i-th group. Let

$$d_{i.} = \begin{pmatrix} d_{i.1} \\ \vdots \\ d_{i.k} \end{pmatrix} = \begin{pmatrix} \sum_{j=1}^{n_i} d_{ij1}/n_i \\ \vdots \\ \sum_{j=1}^{n_i} d_{ijk}/n_i \end{pmatrix} \quad \text{and } D = \frac{1}{\sum_{i=1}^{g} n_i - g} D_{pq}$$

where $D_{pq} = \sum_{i=1}^{g} \sum_{j=1}^{n_i} (d_{ijp} - d_{i.p})(d_{ijq} - d_{i.q})$ is the (p,q)-th element of the matrix D. $d_{i.}$ is referred to as the i-th group centroid and D is the pooled within groups covariance matrix. Then, to classify any sample x_r into one of g groups, k discriminant scores $d_{r1}, d_{r2}, \ldots, d_{rk}$ are computed, and the sample's "χ^2 – distance χ^2_{ir} to the i-th group centroid $d_{i.}$" is obtained from

$$\chi^2_{ir} = (d_r - d_{i.})' D^{-1} (d_r - d_{i.}) \quad \text{for } i=1,2,\ldots,g \tag{8}$$

where $d'_r = (d_{r1}, d_{r2}, \ldots, d_{rk})$. The probability p_{ir} (posterior probability) that the sample x_r belongs to the i-th group, given equal probabilities, is computed by

$$p_{ir} = \frac{\exp(-1/2\ \chi^2_{ir})}{\sum_{j=1}^{g} \exp(-1/2\ \chi^2_{jr})} \quad \text{for } i=1,2,\ldots,g \tag{9}$$

The sample x_r is assigned to the q-th group when p_{qr} is the largest among $p_{1r}, p_{2r}, \ldots, p_{gr}$.