GEOCHEMISTRY AND CLASSIFICATION OF

AMPHIBOLITES AND RELATED ROCKS

GEOCHEMISTRY AND CLASSIFICATION OF AMPHIBOLITES AND RELATED ROCKS

By

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SCOPE AND CONTENTS: Amphibolites from several localities have been studied chemically. The rocks were spectrographically analyzed for Cr, V, Ni, Co, Sc, Zr, Sr, and Ba and major element analyses were done on 20 amphibolites, sediments, and igneous rocks. The chemistry of sediments and igneous rocks which might isochemically metamorphose to amphibolite has been studied. Discriminant function analyses were performed on major and minor elements to classify rocks of known and unknown origins.

ABSTRACT

Amphibolites from 12 localities have been studied chemically with regard to major and minor elements. Discriminant functions have been calculated using rocks of known origin in an attempt to classify amphibolites of undetermined origin. Amphibolites may be classified with a good degree of confidence within a geochemical province by a discriminant function calculated on data for rocks of known origin. Cr, V, Ni, Co, Sc, Zr, Sr, and Ba were used in the discriminant function analysis. Major elements do not appear to be very useful to distinguish amphibolite origins.

Sediments have been analyzed for major and minor elements in an attempt to find materials which might isochemically metamorphose to amphibolite. Mafic graywackes seem suitable and certain argillites also approximate amphibolite in composition.

Niggli number plots are discredited as a means of determining the parentage of amphibolites.

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INTRODUCTION

Amphibolites have long been recognized as having been derived from either igneous or sedimentary rocks through metamorphism. Identification of the pre-metamorphic origin is often difficult because of similarities in the two types.

Work by Kudo (1962) demonstrated the possibility that the chemical composition of amphibolite is a suitable guide to its origin, provided that the several independent chemical variables are considered simultaneously by the multivariate statistical procedure known as discriminant function analysis. Such a procedure is innately superior to the traditional approach of two-dimensional scatter diagrams, and is in fact the extension of such a method to many dimensions.

The purpose of this investigation has been twofold. First, to test the discriminant functions calculated by Kudo (1962) in order to examine the universality of their application. It was decided that, if necessary, new discriminant functions would be calculated so as to obtain better classifications of amphibolites. The second objective was to study the chemistry of geologic materials which might isochemically metamorphose to amphibolite, particularly sediments and tuffs. In the course of the investigation, the methods used by other researchers on amphibolites have been considered and their relevance evaluated.

Acknowledgments

Professor D.M. Shaw suggested this study and with his guidance and assistance it has been completed. Many people have contributed samples or have helped in obtaining them. R.S. Fiske and K.J. Murata of the U.S. Geological Survey were especially helpful in providing information on tuffs and sediments and where to obtain them. G.E. Pattenden gave valuable assistance with the spectrographic analytical work. To these and all those who have contributed to the study with samples, suggestions and discussion, I express my gratitude and appreciation.

Definitions of Terms

The definitions used in this study are from those listed by Shaw (1957). Some of the definitions pertinent to this investigation are as follows:

Amphibolite: A metamorphic rock of medium to coarse grain, containing essential amphibole and plagioclase. Amphibolites are commonly massive and the amphibole often has an elongated or acicular habit, but some varieties can be classed as schist or gneiss. Many amphibolites also contain pyroxene, mica, epidote, or garnet and can be prefixed accordingly. Quartz is also a common constituent.

The prefix Ortho. Of igneous origin: thus an ortho-amphibolite (abbreviated oA) is an amphibolite derived from an igneous rock.

The prefix Para. Of sedimentary origin: therefore para-amphibolites (abbreviated pA) are derived from sediments.

Para-amphibolites and metasomatic amphibolites: In this paper the term para-amphibolite is used as meaning an amphibolite formed by metamorphism of a sediment with essentially no chemical changes other than expulsion of volatile components such as H_2O and CO_2. Such conditions of metamorphism are possible and likely as demonstrated by Coleman and Lee (1963) and Shaw (1956).

Metasomatic amphibolites have formed from igneous or sedimentary rocks with accompanying changes in chemical composition, specifically involving addition and subtraction of non-volatile components. Examples of such changes are described by Leith and Harder (1908), Adams (1909), Grout (1937), Crowder (1958) and Walker et al. (1960).

There is often no clear distinction between these three types on megascopic and microscopic evidence. It is not known whether all the para-amphibolite samples supplied to the author are of undisputed sedimentary origin, but this has been assumed to be the case.

Tuff is considered as a sediment throughout this study although some chemical characteristics appear to be analogous to igneous rocks.

REVIEW OF THE AMPHIBOLITE PROBLEM AND CHEMICAL APPROACHES TO ITS SOLUTION

General

The amphibolite problem results from the difficulty of determining which of several diverse origins is appropriate to a particular amphibolite. Flawn (1953, p. 144) gives the following hypotheses for consideration of amphibolite origins:

"(1) By thermal-kinetic (regional) metamorphism of sedimentary rocks: (a) impure carbonate rocks or marls; (b) tuffs or reworked tuffaceous material; (c) uncontaminated detritus from a basic igneous terrain.

(2) By thermal-kinetic (regional) metamorphism of basic intrusive or extrusive rocks.

(3) By action of hydrothermal or igneous agencies on carbonate rocks; additive (and subtractive) metamorphism.

(4) By the action of a 'basic front' produced by granitization; regional metasomatism."

Similar hypotheses are considered by Engel (1956) and Engel and Engel (1951, 1962), Wilcox and Poldervaart (1958), Evans and Leake (1960), and Walker et al. (1960). Examples of metasomatic amphibolites which are alterations of marble by contact effects adjacent to granites were described by Adams and Barlow (1910) in the Haliburton-Bancroft region of Ontario. Grout (1937) has demonstrated the alteration of shales and slates to rocks of amphibolitic composition upon inclusion in gabbro. Hewitt and James (1956) and Tilley (1958) have described metasomatic amphibolites from the Grenville Province of Ontario.

The major and minor element chemistry of many amphibolites is similar to that of basic igneous rocks such as diabase, gabbro and basalt as shown by Francis (1958), Engel and Engel (1962), Walker et al. (1958), Evans and Leake (1960), and Wilcox and Poldervaart (1958). Massive amphibolites and those which have relict igneous textures and structures which are suggestive of a magmatic origin (e.g. Dodge (1942), Hague et al. (1956), Thomson (1948)) usually provide little difficulty in identification. Those amphibolites which exhibit no evidence of their pre-metamorphic textural and structural nature are the problematical ones.

From a survey of the literature, it appears that para-amphibolites may be difficult to identify with certainty. Thin, banded and otherwise inhomogeneous amphibolites which occur within strata definitely of metasedimentary origin (e.g. Poldervaart and Bentley, 1959, p. 3) are probably the best examples of para-amphibolites. Banded or "striped" amphibolites within metasediments are commonly assumed to be of sedimentary origin.

Eckelmann and Poldervaart (1957) and Poldervaart and Bentley (1959) identified para-amphibolites on their interbedding relations with argillites, quartzites and banded ironstones. Feather amphibolites in marble are considered to be of metasedimentary origin by Adams (1909) and Adams and Barlow (1910). Aquagene tuffs (Carlisle, 1963) have been suggested as progenitors of para-amphibolites.

In a study of metamorphic rocks in Colorado, Boyer (1962, pp. 1053-1954) presents the following discussion of evidence for the origin of mafic gneisses:

> "The hornblende gneisses and some amphibolites are metasedimentary; original sedimentary features are obscured by metamorphic textures. A sedimentary parentage is indicated by accessory epidote and tourmaline; mineralogical banding of biotite, hornblende, oligoclase and quartz; rounded grains of accessory zircon; abundance of quartz; and concordant field relationships. Most likely the parent rock was mixed calcareous and argillaceous sediments. Other amphibolites had a mafic igneous parentage; they show almost equal amounts of hornblende and oligoclase with no other essential minerals or any segregation, or banding. Probably these represent mafic volcanic rocks or possibly sills interlayered with the sedimentary rocks."

The banded nature of amphibolites may however also be of tectonic origin as suggested by Evans and Leake (1960). Thin bands of amphibolite in metamorphic rocks may also result from metamorphic differentiation (Eskola, 1932, Orville, 1963).

Tilley (1957, pp. 347-352) has described amphibolites formed from limestone in Grenville rocks in Ontario. He states:

> "... a passage can be traced from pure limestone to hastingsite-limestone to hastingsite-plagioclase assemblage with subordinate calcite. ... Furthermore, there seems clear evidence that both plagioclase and the mafic mineral are frequently replacing calcite ... their bulk compositions suggest that the fluids which transformed the original limestones brought in not only soda and alumina and silica but also iron."

Tilley (ibid, p. 356) indicates that a syenitic magma source provided the metasomatizing fluids in the area.

Similar metasomatic alteration of limestone adjacent to an andesite laccolith is described by Leith and Harder (1908).

Simonen (1957, p. 55) describes diopside amphibolites from southern Finland and says of their origin: "These stratified rocks have been originally marls in which the detrital material has been deposited simultaneously with calcium carbonate."

In the laboratory various methods have been employed in attempts to distinguish between amphibolites of meta-igneous and meta-sedimentary origin. Carlson (1920), Turner (1951) and Gorai (1951) have suggested feldspar twinning differences in igneous and metamorphic rocks as one approach to solution of the problem. Walker et al. (1960) and Evans and Leake (1960) used these methods with little success. Magnetic properties were studied by Walker et al. (1960) with inconclusive results. Most attention has been given to the use of chemical analyses, as discussed in the following section.

Chemical Methods

The study of amphibolites by modern chemical methods was initiated by Engel and Engel (1951). They state:

> "Clues to the derivation of amphibolites seem to exist ... in their differential inheritance of accessory elements. Amphibolites derived from mafic igneous rocks, for example, are, like their parents, commonly higher in Co, Ni, Cr, Sc, and Cu and lower in Pb, Au, and Ba than amphibolites derived from carbonate sediments. ... Apparently dynamothermal metamorphism of the gabbros does not remove the initial concentrations of Sc, Cr, Co, Ni, and Cu as rapidly as it obliterates other diagnostic properties. Conversely, amphibolites derived by replacement of marbles tend to maintain higher concentrations of Ba, Pb, and Au than many known ortho-amphibolites".

This initial study of trace elements in amphibolites has given rise to further investigations along similar lines. Wilcox (1955) and Wilcox and Poldervaart (1958) concluded that Ga, Ba, Ni, Co, and Cr do not serve as valid distinguishing criteria for separating ortho- from para-amphibolites. In the amphibolites they studied, Sr was significantly different in the two types, being in lower abundance in the para-amphibolites. Engel (1956) found that major element abundances were not useful in dis-

tinguishing amphibolites with regard to their origins. In a study on amphibolite interlayers in paragneiss of the Northwest Adirondacks, N.Y., Engel and Engel (1962, pp. 68-69) conclude that " ... analyses of trace elements and of major elements ... seem to demonstrate effectively that the amphibolites in the gneiss complex have bulk chemical compositions like many mafic rocks of extremely diverse origin." They further state (ibid, p. 69) "Some of the apparent similarities in composition of amphibolites derived from different parent rocks might disappear with an increase in the precision and accuracy of the analyses. But until existing errors of analyses are greatly reduced and interlaboratory standards are employed, trace-element studies cannot be a powerful tool in genetic studies of amphibolites, or other rocks".

Eckelmann and Poldervaart (1957) found trace element analyses of little value in showing differences between ortho- and para-amphibolites in the Beartooth Mountains. The present study indicates that the Beartooth amphibolites studies by Poldervaart and co-workers are quite different as a group from amphibolites from other areas, especially in their trace-element character (see later).

Turekian (1963, pp. 4-6) also states a negative opinion on the value of trace-element analyses as a guide to the interpretation of amphibolite origins. He considers Li, Be, B, As, Rb, Sn, Sb, and Cs as the best elements which might give clues to amphibolite origins. He cautions that ... "these elements are also likely to be highly mobile in the wet metamorphism presumably involved in the formation of amphibolites". The concentration of Sn was measured in several shales and basalts but no cor-

relation was found between Sn content and mode of origin of the rocks. Shale was discussed because it was considered to be the most important sediment contributing to amphibolite in bulk composition.

Skiba and Butler (1963) studied plagioclase from gabbro, metagabbro and amphibolites interlayered with gneisses, considering the Sr and anorthite contents of the plagioclases. The Sr content of the plagioclases in the gabbros is almost invariably in the range 1000-1450 ppm. The country rock amphibolites adjacent to the gabbros have more variable Sr content in plagioclase, generally below the 1000-1450 ppm range. Skiba and Butler found the method useful in separating metagabbros from host rock amphibolites. The results suggest that the observed differences may reflect differences in the mode of origin of the rocks and the method might be useful in distinguishing ortho- from para-amphibolites.

Lapadu-Hargues (1953) studied the major element chemistry of 89 amphibolites and found bimodal distributions for FeO, MgO, CaO, and Na_2O. These were interpreted as correlative with type of amphibolite, i.e. ortho-amphibolites are higher in FeO and lower in MgO, CaO, and Na_2O. Wilcox and Poldervaart (1958, p. 1362) note that the bimodal peaks for these four oxides are not formed by the same rocks and that the average olivine basalt from the Pacific (from Green and Poldervaart, 1955) is identical with the type para-amphibolite of Lapadu-Hargues in terms of FeO, MgO, CaO, and Na_2O. Later, (1958) Lapadu-Hargues considered TiO_2 as an indicator of amphibolite origins, stating that most para-amphibolites contain less than 0.8% TiO_2 and most ortho-amphibolites greater than 0.8% TiO_2.

Walker et al. (1960) studied amphibolites which had undergone metamorphism and metasomatism in an attempt to find a way of distinguishing their origins. Analyses for Co, Cr, Cu, and Ni show marked differences between igneous rocks and para-amphibolites which have suffered minimal metasomatism. Where metasomatic effects are great, the para-amphibolites appear to assume an ortho-amphibolite complexion chemically.

Amphibolites from the Lead-Deadwood area of South Dakota were studied by Raychaudhuri (1960) who concluded (p. 63), "The major, minor, and trace element compositions of the amphibolites of the Lead-Deadwood area do not show any specific evidence pointing to a definite origin".

Heier (1962) studied several amphibolites on the island of Langøy, Norway and found that separation into two groups was possible using the trace element distributions. Ni and Cr appear to be the best elements for showing differences, being markedly lower in abundance in presumed para-amphibolites used in his study.

The U and Th contents in amphibolites were measured by Billings (1962) in an unsuccessful attempt to show differences between possible para-amphibolites and presumed ortho-amphibolites from the Llano area of Texas.

Evans and Leake (1960) and Leake (1963, 1964) have used chemical analyses (major and trace elements) and Niggli number plots of major element data in attempting to determine amphibolite origins. This method is invalid in the light of an evaluation described elsewhere in this paper (pp.11-16).

In summary, it appears that the evidence is quite conflicting as to whether a comparison of single element abundances is of help in interpreting amphibolite origins. In analogous situations in paleontology and psychology much success has been obtained when methods are used which permit the simultaneous consideration of several variables, suggesting the use of such procedures in the present problem.

For example Kudo (1962) used multivariate statistical methods. Amphibolites of known origin from Chandos Township, Ontario, were analyzed for Cr, V, Ni, Co, Sc, Sr, Ba, and Zr and the data were used for computing a linear discriminant function. Using the function it was possible to classify correctly many rocks of known origin. The elements which gave the most effective discrimination are Co, Sc, Fe^{2+}, P, and Ti. With trace elements alone the most effective results were obtained using all eight elements.

The present investigation is an amplification of Kudo's work using amphibolites from widely spaced localities to assess the effect of provincial variations. In addition, sediments which might produce amphibolites through regional metamorphism have been chemically studied.

Niggli Number Plots

Before discussing in detail the results of the present study, it is desirable to examine further a method in which two chemical variables were considered simultaneously by use of scatter diagrams.

Evans and Leake (1960) and Leake (1963, 1964) have favored the use of Niggli members calculated from chemical analyses in two-dimensional plots to show similarities between amphibolites and basaltic and sediment-

ary rocks: i.e. if igneous trends are followed on a Niggli number plot, the amphibolites in question are said to be of igneous origin. If the igneous trends are not followed, the rocks are interpreted as being of metasedimentary or possibly metasomatic origin.

Analyses of the Karroo Dolerites by Walker and Poldervaart (1949) were used to establish the igneous trends. Hypothetical sedimentary trends were established using pelite, limestone, and dolomite analyses. No suites of known para-amphibolites were investigated by Evans and Leake.

Because of the similarity of the major element abundances in both ortho- and para-amphibolites, it may be reasoned that any transformations of major element abundance data will retain these similarities. Hence it seems unlikely that Niggli number plots could be useful in distinguishing between ortho- and para-amphibolites.

Two groups of para-amphibolite analyses (Beartooth Mountains (13), and Chandos Township (11)) were available in this study so it was decided to plot their Niggli numbers in the manner of Evans and Leake to find out whether they show non-igneous trends. Plots of c against fm and c against al-alk for the Chandos para-amphibolites show some of them following Karroo trends and others not. All of the Beartooth para-amphibolites followed the Karroo trends. Therefore, it appears that Niggli number plots for major elements are useless in determining amphibolite origins (see fig. 1,2).

Minor elements were also considered by Evans and Leake and the following is stated by Leake (1963, p. 1194), "Plots of Cr and Ni against mg are conclusive in deciding the origin of amphibolites ... There is

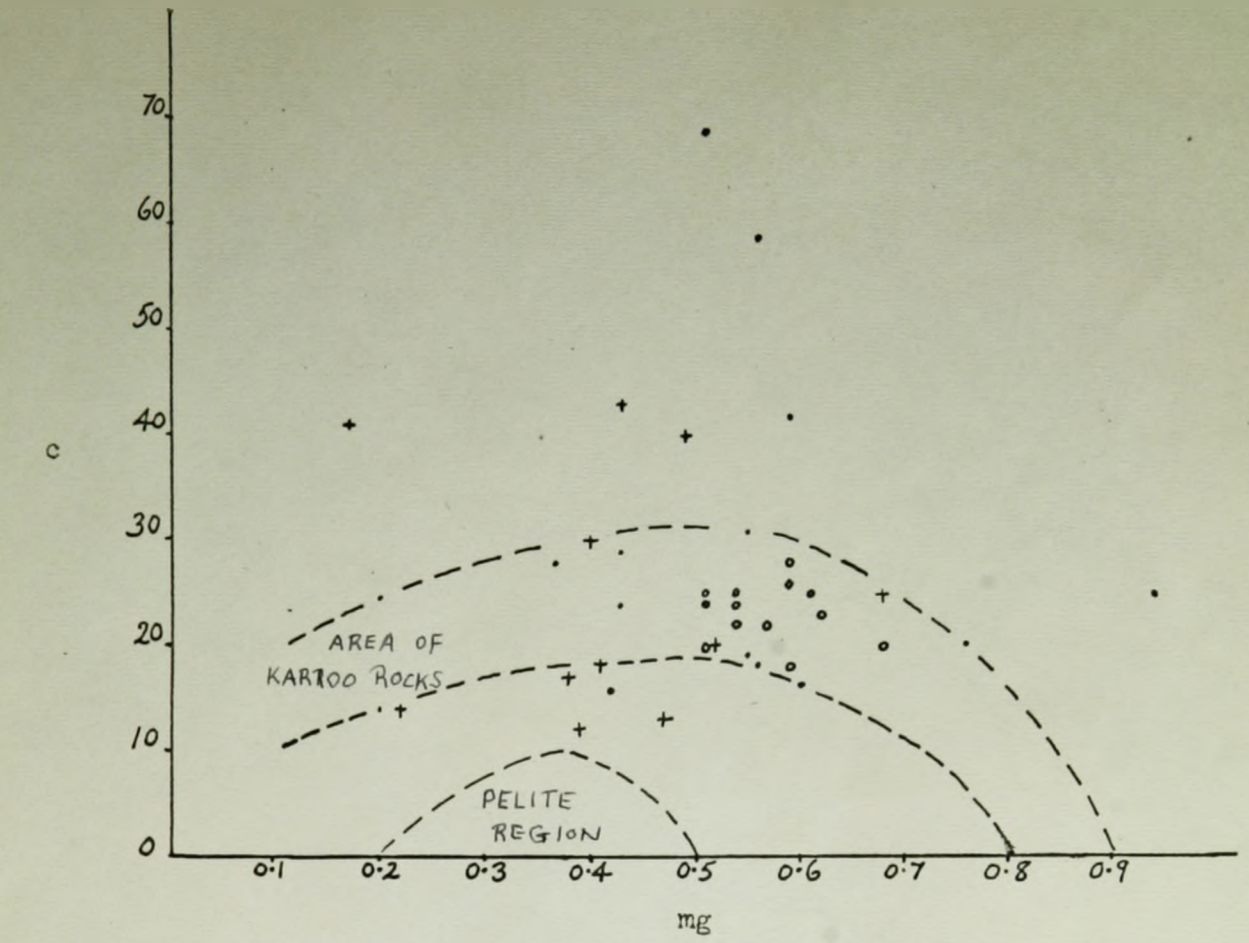
a positive correlation of Cr with mg and of Ni with mg, which almost precisely agrees with the correlations shown by the Karroo dolerites, whereas para-amphibolites should give negative correlation". It is not clear why a negative correlation should be characteristic of para-amphibolites.

Plots of Cr against mg (Fig. 2) and Ni against mg (Fig. 3) with data for the Beartooth and Chandos para-amphibolites indicate that positive correlations exist and furthermore, these plots overlap those for the Connemara, Adirondack, and Karroo rocks. Thus the evidence shows that these plots are of no value in determining amphibolite origins.

Because amphibolites are commonly of basaltic composition, whether of meta-igneous or meta-sedimentary origin, they will give Niggli number plots similar to those for basic igneous rocks. Those amphibolites with compositions greatly different from basalt will not plot close to the basaltic rocks and such differences are usually obvious without plotting transformations of analytical data.

It is concluded that two-dimensional analysis is of little general value in the present problem, although this procedure would undoubtedly be useful where two clear-cut groups of amphibolites occur as in the case of the Chandos rocks examined by Kudo (1962).

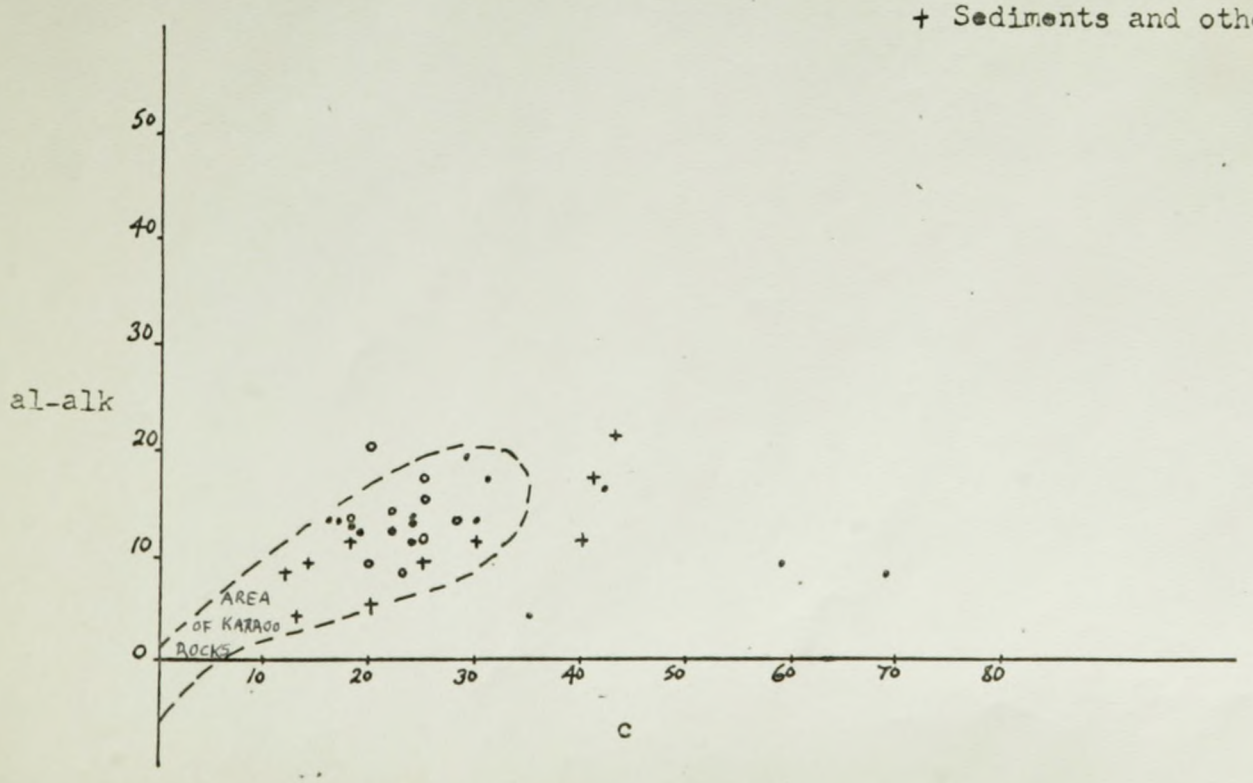
Figure 1. Niggli Number Plots for Para-amphibolites



• Chandos Twp. pA

o Beartooth Mtns. pA

+ Sediments and other pA



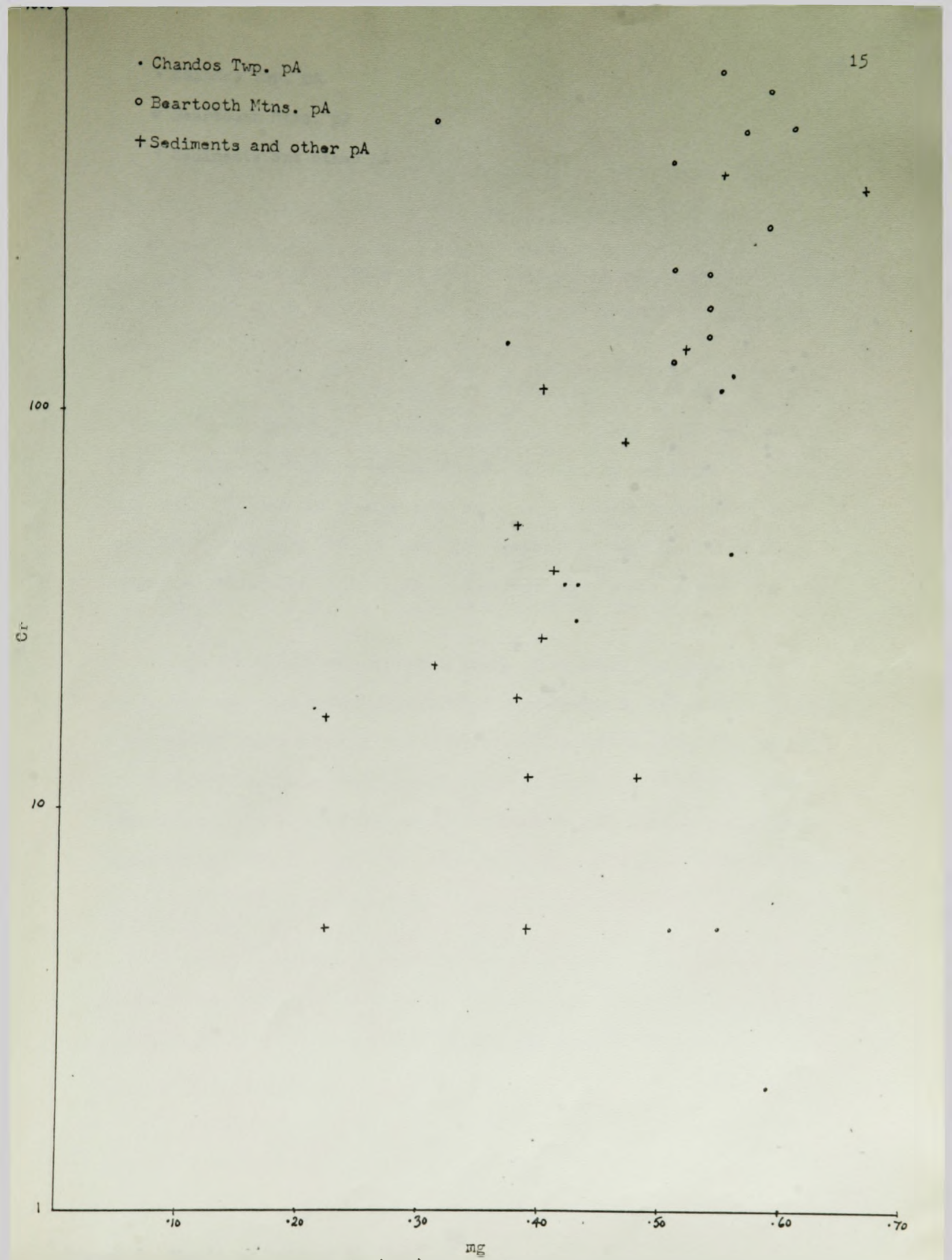


Figure 2. Niggli mg against Cr (ppm).

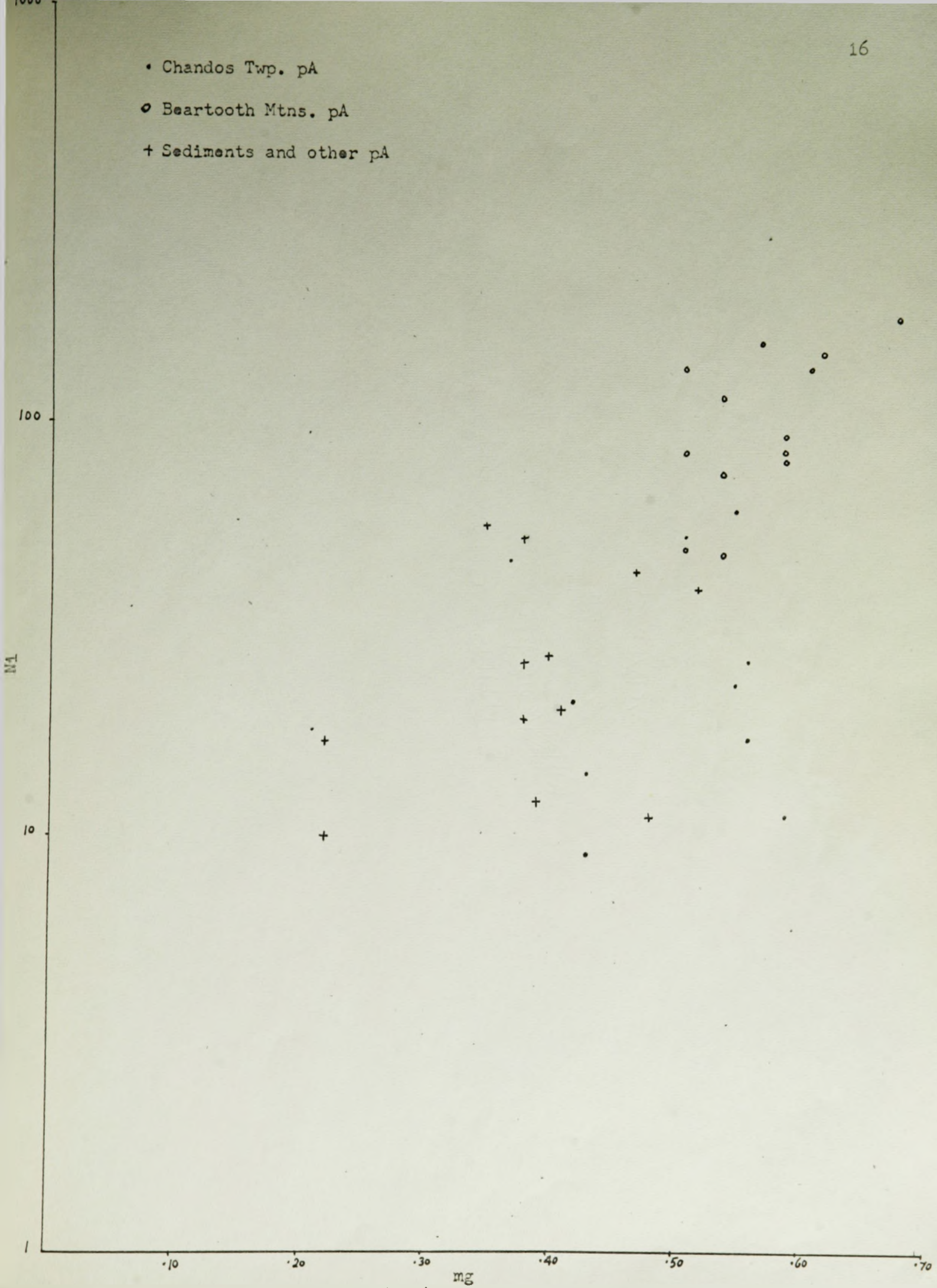


Figure 3. Niggli mg' against Ni (ppm).

SAMPLES

One of the objectives of this investigation was to examine chemically those rock types which have been suggested as parental to amphibolites and to examine some of the metasomatic types.

The sedimentary rocks which might closely approach amphibolite in composition are mafic graywacke and mafic tuff. Samples of these were obtained from the western United States and analysed for major and trace elements. Graywackes from an area of low- to intermediate-grade metamorphism in southern Ontario were also examined chemically. Argillites were also considered. No impure carbonates of suitable composition could be located.

In addition a miscellaneous group of amphibolites whose mode of origin had been determined geologically were analysed. The data obtained were used in calculation of the discriminant functions which were used to classify amphibolites of unknown origin. A summary of localities and samples is given in table 1; detailed information on the samples is in Appendix 2.

Sources of Samples

Amphibolite samples from the Beartooth Mountains of Wyoming and Montana were generously provided by R.D. Bentley. These include samples collected by F.D. Eckelmann, R.H. Harris, and R.D. Bentley.

G.K. Billings sent fourteen samples of the Packsaddle schist from the Llano Uplift area of Texas. Six samples of the Connemara amphibolites were sent by B.E. Leake. Samples from Broken Hill, Australia were contributed by R.A. Binns. J.C. Cummings provided the tuffs and altered lava from Oregon. Another tuff and a basalt sand from Hawaii were sent by K.J. Murata. Dr. Murata also assisted in obtaining other samples. Mafic graywackes from the Pacific coast of Oregon and Washington were sent by P.D. Snavely. F.B. Van Houten contributed three samples of the Lockatong argillite.

The samples from New Jersey, New York, and Kirkland Lake, Ontario were collected by the author. S.B. Lumbers assisted in obtaining samples from Limerick and Dungannon Townships in southeastern Ontario.

Preparation of Samples

The rocks from Texas, the Beartooth Mountains, Ireland, and Australia arrived in powder form.

All the other samples were crushed and pulverized by the author. A Bico-Braun Jaw Crusher and Pulverizer were used to reduce the rocks to about 50 mesh size. Then splits of the samples were made using a Jones-type riffle splitter to obtain 100 gram samples for final pulverizing to 100 mesh and smaller size for chemical analysis. Splits were made of the powders so obtained to provide samples for wet chemical and spectrographic analyses.

Spectrographic Methods

A spectrographic analysis procedure using a buffer-internal standard mix developed by G.E. Pattenden was employed in this study. The buffer-

TABLE 1

Samples used in this study

Para-amphibolites

Locality	Number of Samples
Hibernia, New Jersey	3
Dungannon Township, Ontario	1
Chandos Township, Ontario	6
Beartooth Mountains, Wyoming and Montana	13

Ortho-amphibolites

Hamburg, New Jersey	3
Elizabethtown Quadrangle, New York	2
Teck Township, Ontario	2
Chandos Township, Ontario	6
Broken Hill, Australia	1
Beartooth Mountains	8

Metasomatic amphibolite

Madoc Township, Ontario	1

Amphibolites of uncertain origin

Beartooth Mountains	4
Llano Uplift, Texas	14
Connemara, Ireland	6
Broken Hill, Australia	9

Sediments and Igneous Rocks

Locality	Rock	Number of Samples
New Jersey	Argillite	3
Hawaii	Basalt sand	1
La Honda, California	Tuff	1
Western Oregon and Washington	Graywacke	2
Western Oregon	Tuff	3
" "	Lava	1
Limerick Township, Ontario	Graywacke (low- to intermediate-metamorphic grade)	3

standard mix contains 49.85% United Carbon Products graphite, 0.025% $PdCl_2$, 0.125% In_2O_3 and 50.00% Cs_2CO_3. After weighing on a precision balance and hand mixing of the mix in an agate mortar, the mix was placed in a clear plastic container with two plastic balls and homogenized by mixing for two hours in a Spex Industries Mixer-Mill. The mix was then dried for three hours in a sand bath at 200°F and then stored in a desiccator. Samples were prepared for analysis by mixing with acetone in an agate mortar one part sample to one part buffer-internal standard mix.

Working curves prepared by G.E. Pattenden for this method were used. Data on these is provided in table 2.

The entire spectrographic method is outlined in detail in table 3.

Precision of the spectrographic analyses

Precision of the spectrographic analyses was calculated using a single-factor analysis of variance method programmed for the I.B.M. 7040 computer by D.M. Shaw and G.A. Riley. To determine the precision of replicate analyses the mean square "within analyses" was computed as the best estimate of the population error variance σ^2. The pooled estimate of the error variance, Sp^2, was then computed from analytical data transformed to logarithms. The log concentration values were used because it was apparent from analytical results that analytical error is a function of the magnitude of the absolute concentration. Sp^2, the pooled variance, is used to compute the analytical precision (estimated by the standard error, S, of the mean),

TABLE 2

Working Curve Data

Element and Standard	Range of Curve (values in ppm.)
V 3183.9/Pd 3242.7	20 - 2000
Zr3391.9/Pd 3242.7	20 - 1200
Ni3414.7/Pd 3421.2	10 - 1000
Co3453.5/Pd 3421.2	10 - 1000
Sc3911.8/Pd 3609.5	20 - 1000
Cr4254.3/Pd 3609.5	10 - 1000
Ba4554.0/In 4511.3	30 - 1000
Sr4607.3/In 4511.3	30 - 1000
Mn4041.3/Pd 3609.5	1000 - 10000

TABLE 3

Details of the Spectrographic Method

Spectrograph:	JACO 21 foot grating spectrograph, Wadsworth mount, first order dispersion 5.2 A/mm.
Condensing Optics:	(distances are from the slit) 0.0 cm. Cylindrical lens (horizontal axes) Focal length 25 cm 16.1 cm. Cylindrical lens (vertical axes) Focal length 6.7 cm 27.5 cm. Diaphragm with 5 mm. aperture 58.1 cm. Spherical lens, focal length 10 cm 72.5 cm. Arc location
Arc Gap:	4 mm.
Slit Width:	30 microns
Slit Height:	8 mm.
Intensity Reduction:	By 7-step rotating sector (log intensity ratio = 0.2) at the slit. Two mesh screens used at the diaphragm
Voltage:	225 volts D.C., open circuit
Current:	9.5 amps
Exposure:	Samples burned to completion (60-100 seconds burning time)
Electrodes:	Anode: United Carbon Products Co. preformed 1/8" diameter rod; plain crater 1/16" x 3/8" Cathode: National Carbon Co., special graphite; 1/8" diameter rod
Gas Jet:	Stallwood jet used with Ar-O_2 mixture in ratio 79:21 (supplied mixed in pressure tank by Canadian Liquid Air Co. Ltd.) at 18 s.c.h.f.
Cooling:	Water at 15 g.p.h.
Photographic Plates:	Eastman Kodak Type S.A.I (range 2400-3600 Å) " " " IIIF (range 3600-4800 Å)

TABLE 3 (continued)

Processing:	Kodak D-19 Developer, 3 minutes at 20°C Fixer, 5 minutes Wash in water bath, 30 minutes
Photometry:	JACO microphotometer, three steps measured, background set to 100 on first step read, correction read on third step.

$Sp^2 = nS^2$ where n = number of replicates for each sample

so for triplicate analyses $S^2 = \frac{Sp^2}{3}$.

Approximation of the arithmetic coefficient of variation, C is made from S^2 as follows:

$\bar{x} + S$ = the upper limit, U,

and $\bar{x} - S$ = the lower limit, L.

Then $\frac{\text{antilog U - antilog L}}{2}$ gives an approximate standard error (S) of the mean ($\bar{k}$) in arithmetic units. C gives the relative error for triplicate analyses as

$C = \frac{100\ S}{\bar{k}}$. These values are listed as percentages in table 4. The sums of squares and mean squares are in table 17.

The log transformation of the data is advantageous because a linear relation exists between log k and y but not for arithmetic k and y. Thus for similar absolute deviations y's throughout the range for a particular element, there are similar absolute deviations in the log k values but not in arithmetic k values.

TABLE 4

Precision of Spectrographic Analyses for triplicate analysis

Element	Precision (%)
Cr	15.1
V	12.4
Ni	6.4
Co	6.7
Sc	13.0
Zr	17.2
Sr	14.9
Ba	18.1

Accuracy of the Spectrographic Analyses

There is no absolute measure of the accuracy of the spectrographic analyses. The standard rock for analysis, W-1 has been used as a standard in this study because of its overall chemical similarity to amphibolite. The results of analyses of W-1 by the author and Kudo (1962) are given in table 5 with the recommended values of Fleischer and Stevens (1962).

TABLE 5

W-1 Analyses

	Fleischer and Stevens	This Study	Kudo (1962)
Ba	225	160	202
Co	52	48	35
Cr	120	160	114
Ni	80	66	53
Sc	33	44	21
Sr	220/175	145	194
V	240	270	217
Zr	100	100	92

Although the Ba, Sr, and Ni values are lower than the recommended values and Cr and V are higher, it was judged unnecessary to make adjustments to the analyses. If adjustments were desired, they could be made by multiplication by the ratio of the two values in table 5.

Previously Analyzed Rocks

Some of the samples used in this study had been analyzed for trace-elements by other workers. These include the Beartooth amphibo-

lites, the Connemara, Broken Hill, Chandos, and Packsaddle schist samples, but not all analyses include all the elements used in this study. In order to obtain uniform relative abundances of elements among the samples, it was necessary to analyze some of the samples by the method described. All the Connemara, Broken Hill, and Packsaddle schist samples were re-analyzed and 10 of 25 Beartooth samples were done. Conversion factors, which were the ratios of the appropriate averages listed in table 6, were used to change values on the remaining Beartooth rocks to conform with those analyzed. The Chandos and Adirondack samples were analyzed by Kudo (1962) and the trace-element values for these were converted by using W-1 analysis values of Kudo and of this study. Averages of trace element abundances obtained by other workers and by the author on the same rocks are in table 6.

TABLE 6

Average trace-element abundance values in rocks previously analyzed

	Connemara Amphibolites (6)		Beartooth Amphibolites (10)		Broken Hill Amphibolites (10)		Packsaddle Schist (14)	
	Evans & Leake	van de Kamp	Joensuu	van de Kamp	Allen	van de Kamp	Billings	van de Kamp
Cr	97	103	390	391	36	41	100	271
Ni	50	47	134	109	32	51	67	98
Co	26	34	38	42	39	58	13	50
Sc	35	44	118	203	32	56		
Zr	199	306	96	127	110	173		
V	n.a.	322	157	223	344	379		
Sr	187	104	248	246	63	120	145	205
Ba	248	93	245	174	128	115		

In the case of Cr, Ni and Co the author's results agree well with other analysts except Billings, whose figures are low. There is less agreement for the other elements listed in table 6 and it was therefore deemed advisable to restrict further discussion to the author's data, which (whether right or wrong) were obtained in one laboratory by one method.

POSSIBLE PARENTS OF AMPHIBOLITES - CHEMICAL CONSIDERATIONS

As with petrographic and mineralogic aspects, compositional similarities in the chemistry of ortho- and para-amphibolites make difficult the distinction between the two types. In general, most amphibolites have bulk compositions similar to basaltic rocks, as illustrated by averages (A-D) in table 7. The following discussion deals with the chemical aspects of amphibolites and some possible parent rocks.

Igneous Rocks

In contrast to the problems of understanding the genesis of para-amphibolites, it is relatively simple to understand how ortho-amphibolite may be formed. Gabbro, basalt, and basic andesite are chemically similar to many amphibolites with regard to major and minor elements. Water may be added upon metamorphism to amphibolite but unless further metasomatism occurs, ortho-amphibolites may be considered as identical to basic igneous rocks for most purposes. In fact, under high water pressure, a basaltic magma will yield amphibolite upon crystallization (Yoder and Tilley, 1962, p. 459).

The trace element abundances for the average basaltic rock (table 7, D) are similar to those for the average of 16 ortho-amphibolites except for Cr and Sc which are lower and Sr and Ba which are higher. These differences may be due to metamorphic effects or analytical errors. A larger amphibolite sample might give more comparable results or else substantiate differences shown here.

The preceding summary shows that derivation of amphibolite by isochemical metamorphism of basaltic rocks is a relatively simple matter. Problems of derivation of amphibolites from sedimentary rocks are reviewed below.

Sedimentary Rocks

Some investigators of amphibolites (e.g. Edwards, 1957; Adams, 1909; Kalsbeek, 1962; Shaw, 1962; Eckelmann and Poldervaart, 1957; and Evans and Leake, 1960) have suggested various sedimentary rocks which might be metamorphosed isochemically or metasomatically to amphibolites. Few of those who have studied amphibolites have attempted to demonstrate quantitatively how sediments may be transformed into amphibolites metamorphic and metasomatic processes.

In reviewing the literature on the subject, it is found that the most commonly suggested sedimentary parents to amphibolite are shale enriched in Mg and Ca, marl, impure argillaceous limestone and dolomite, and mafic graywacke. Comparison of these sediments with amphibolite shows that most are chemically unsuitable for isochemical metamorphism to amphibolite for reasons outlined below.

Shale. In amphibolite the Na_2O/K_2O ratio is normally greater than unity whereas in shale it is generally less. Al and Si are more abundant and Fe, Ca, Mg are less abundant in most shales (analyses E and F in table 7). Some shales more closely approximate amphibolite except for the Na_2O/K_2O ratio as demonstrated by analyses G and H in table 7.

It is apparent that considerable alteration of shales upon metamorphism is necessary to produce amphibolite. Rocks such as G and H, table 7 would require the addition of Fe, Mg, and Na and subtraction of K. Grout (1937, pp. 1521-1572) demonstrated that shales and slates altered towards an amphibolitic composition when included in gabbroic magmas. He (ibid, pp. 1545-1546) showed that Si, Al, and K were lost in metasomatism of the slates while Fe, Mg, Ca, and Ti were added. The net result is a hornfels with the composition of amphibolite. It may be possible for similar metasomatism to take place on a large scale during regional metamorphism to produce amphibolite from shales. However the common occurrence of isochemically metamorphosed shales shows this to be unlikely.

Orville (1963) has suggested a mechanism by which the Na/K ratio in carbonate-bearing shales might be altered during metamorphism. It is explained as follows:

> "The large variability of CaO compared to that of the alkalies (Na_2O and K_2O) ... can be explained if shales are considered to consist largely of argillaceous material of relatively uniform composition, combined with a small but variable amount of carbonate material. Under conditions of moderate to high-grade regional metamorphism it is reasonable to suppose that a major part of the Ca originally combined with carbonate becomes incorporated in plagioclase together with Na and that at least part of the K in the rock occurs in a K-feldspar phase. ... assuming that an alkali-bearing vapor phase is present, Na and K will be exchanged between Ca-rich and Ca-poor layers. If the carbonate fraction of the original shale was dolomite, alternating amphibolite layers without K-feldspar and granitic layers containing abundant K-feldspar would be the natural result of this metamorphic differentiation," (ibid, pp. 234-235).

Presumably the creation of such a layered rock would result in mafic components going to the amphibolite and leucocratic components going to the granitic phase.

Sodic argillites were suggested as possible progenitors of amphibolite by Professor A.F. Buddington (pers. comm.). Three samples of the Lockatong argillite from the Triassic lowland of New Jersey were analyzed (table 7, I,J,K) and compared to amphibolites. Although they differ from typical amphibolites with their high alkali-metal contents and low Mg, they are not greatly different and with minor changes would compare chemically to amphibolite. The trace element contents are more characteristic of shales (cf. Turekian and Wedepohl, 1961), table 7,E.

The average abundance of many trace elements in shale is different from basic igneous rocks as shown by Turekian and Wedepohl (1961) but some elements occur in similar abundances in both rock types (e.g. Zn, Zr). Metasomatic additions of mafic components to shale might alter the amounts of trace metals so as to make them comparable to basaltic rock values, thus complicating attempts to decipher the origin of the end product.

Edwards (1957, pp. 19-20) described amphibolites from the Broken Hill area of Australia which have low Al, Na, and Fe and high Mg and Ca abundances. These are quite different from any igneous rock and are believed to be derived from sandy or argillaceous magnesian limestones. Eckelmann and Poldervaart (1957, p. 1251) suggest a similar parentage for the para-amphibolites they describe. Poldervaart and Bentley (1959, pp. 3-4) found that ... "dolomitic shales or graywackes ... form para-amphibolites upon metamorphism. Fine interbedding with quartzite leaves no doubt of the sedimentary origin of these amphibolites".

Graywackes. Kalsbeek (1962) proposed that graywackes derived from basaltic flows might produce amphibolite upon metamorphism. In this study several mafic graywackes have been analyzed (table 7, L-Q).

The Yachats formation of western Washington contains basaltic sandstones or mafic graywackes which appear to be weathering products of basaltic igneous rocks. When the analysis of this rock, Appendix 1, No. 45, is recalculated on a $CaCO_3$-free basis, the rock composition is seen to be similar to amphibolite, table 7, L. The graywackes from Oregon and California also are similar to amphibolite when their analyses (Appendix 1) are considered on a CO_2-free basis (table 7, M, N).

The trace elements are of interest in these rocks (table 7, L, M) and it can be readily seen that Cr, Ni, Co, and Sc are present in lower abundance, than in the average basaltic rock (table 7, D). Comparison with the average trace element contents of 16 ortho- and 16 para-amphibolites shows that the graywackes are similar to para-amphibolites (table 7, B, C, L, M). Mg is lower than the average for basaltic rocks and amphibolites and may represent depletion of Mg in weathering and sedimentation. Similar graywackes from Limerick Township, Ontario (table 7, O, P, Q) also have the chemical characteristics of the graywackes described above.

The Limerick rocks represent the same sedimentary facies at different metamorphic grades. All are limy graywackes; O has been metamorphosed under lower greenschist facies, P at upper greenschist facies, and Q at epidote-amphibolite facies conditions. Some trends worthy of note are the decrease of CO_2 and CaO with increasing metamorphic grade and increase of total Fe, Ti, Mn, Si, and Al. These trends may result from decarbonation, variation in the original sediment, or from metamorphism and metasomatism.

The trace element abundances are similar to those in the other graywackes and more comparable to those in para-amphibolites than in ortho-amphibolites (table 7, B, C, O, P, Q). It is difficult to establish trends on the basis of three analyses but Co and V abundances appear to increase with increasing grade of metamorphism; if they are associated with Fe, they reflect the increase in total iron.

In two graywackes (table 7, L, M), a large portion of Fe occurs in the trivalent state. In the other graywackes (table 7, N-Q), the greater part of Fe is in the divalent state as in para-amphibolites (table 7, C). Aside from this, all the mafic graywackes show many similarities with amphibolites (e.g. Connemara 2506, 2518).

Limestones and Metasomatized Limestones. The classic study of Adams (1909) and Adams and Barlow (1910) cites examples of the transformation of relatively pure limestone to amphibolite in the Grenville province of Ontario. Metasomatism by intrusive granite has added Si, Al, Fe, Mg, Na, and K to the limestone. Ca and CO_2 have been extracted in the metasomatism and the resulting product is amphibolite. The chemical changes are illustrated by analyses S-V in table 7. Analysis R (table 7) is of a partly silicated limestone (similar to S) from Madoc Township, Ontario. The unaltered marble stratigraphically equivalent to this rock appears quite pure so it is apparent that the silicated material in a granite contact aureole has undergone changes similar to those described by Adams and Barlow. Cr, Ni, Co, and Sc in this rock are in very low abundances. With further metasomatism to a carbonate-free amphibolite, it may be expected that the abundances of trace elements would increase as the major mafic components. If it is assumed that the rock is one-third amphibolite and

two-thirds limestone, then it might be inferred that with completion of metasomatism to yield amphibolite would yield trace element abundances much lower than those for ortho-amphibolites. This inference requires further study.

Tuffs. Mafic tuffs have been suggested as being suitable to metamorphose isochemically to amphibolite (Wilcox and Poldervaart, 1958, p. 1363). They are particularly suitable to explain banded amphibolites with great lateral continuity. Such tuffs, deposited in a marine environment might produce para-amphibolites upon metamorphism if the diagenetic effects were sufficient to alter their igneous trace chemical characteristics to give them a sedimentary complexion.

Four aquagene tuffs were analyzed in this study (table 7, W-Z). Their bulk chemistry compares well with amphibolites (table 7, A-C) and the trace elements have abundances similar to those for ortho-amphibolites in some cases and to para-amphibolites in other cases. This indicates that tuffs may have either igneous or sedimentary chemical characteristics.

Summary

From the preceding review it is apparent that only a few geological materials are suitable for isochemical metamorphism to amphibolite. These include mafic graywackes, mafic tuffs, and basaltic igneous rocks. Other sediments would require metasomatic alterations to produce amphibolite. Among these, the Lockatong argillite would require the least change and limestones the greatest. Trace elements in mafic graywackes compare well with para-amphibolites and are distinct from basic igneous rocks. The argillites have trace element abundances analogous to those of para-amphibolites also.

The statistical analysis of data and classification methods for amphibolites are discussed in the following pages.

TABLE 7

Analyses of Amphibolites, Sediments, and Tuffs

	A	B	C	D	E	F	G	H
SiO_2	49.73	49.33	51.51	51.0	58.38	56.30	48.12	46.81
TiO_2	1.39	1.56	0.97	1.4	0.65	0.77	0.78	0.67
Al_2O_3	14.92	14.70	14.74	15.6	15.47	17.24	12.80	14.00
Fe_2O_3	2.97	2.65	2.01	1.1	4.03	3.83	1.60	5.35
FeO	8.77	9.72	7.82	9.8	2.46	5.09	3.25	-
MnO	0.21	0.19	0.17	0.2	-	0.10	0.09	-
MgO	6.57	6.45	6.36	7.0	2.45	2.54	2.55	4.66
CaO	9.51	9.17	10.10	10.5	3.12	1.00	10.77	10.36
Na_2O	2.70	2.79	2.94	2.2	1.31	1.23	0.60	0.34
K_2O	0.98	1.09	1.12	1.0	3.25	3.79	3.60	3.67
P_2O_5	0.25	0.35	0.20	0.2	-	0.14	0.65	0.05
CO_2	0.85	0.87	1.17		2.64	0.84	9.19	9.65
Cr		328	118	170	90			
V		319	220	250	130			
Ni		97	41	130	68			
Co		52	32	48	19			
Sc		54	38	30	13			
Zr		185	183	140	160			
Sr		235	252	465	300			
Ba		232	304	330	580			

A Average of 262 amphibolites (analyses from literature averaged by author)

B Average of 54 ortho-amphibolites (analyses from literature trace elements for 16 am.)

C Average of 42 para-amphibolites (from this study)

D Average basalt:major elements (for tholeiite), Poldervaart, 1955; trace elements, Turekian & Wedepohl, 1961.

E Average shale:major elements, Clarke, 1924; trace elements, Turekian and Wedepohl, 1961.

F Average pre-Cambrian slate (Nanz, 1953).

G Shale, Ordovician, Ohio (Stout, 1941).

H Marl-Shale (Munthe, 1921).

TABLE 7 (continued)

	I	J	K	L	M	N	O	P
SiO_2	49.20	38.24	48.94	49.34	53.35	50.33	37.29	47.85
TiO_2	0.78	0.60	0.81	2.84	2.74	-	0.51	0.86
Al_2O_3	15.99	12.86	17.19	16.59	13.01	14.27	9.34	12.77
Fe_2O_3	1.70	0.72	2.81	7.76	13.71	2.82	0.34	0.81
FeO	3.89	4.75	4.05	5.73	2.00	3.48	3.96	6.29
MnO	0.15	0.15	0.11	0.69	0.27	0.50	0.09	0.10
MgO	3.36	5.79	3.36	4.56	4.40	6.27	3.20	3.67
CaO	6.15	12.90	4.00	6.25	4.58	16.55	23.26	13.85
Na_2O	5.62	3.43	7.35	3.79	3.16	3.79	2.09	2.72
K_2O	3.50	3.64	2.28	1.44	2.07	1.55	1.17	1.17
P_2O_5	0.18	0.17	0.16	0.82	0.64	0.33	0.18	0.24
CO_2	7.06	14.46	4.62		0.10		17.86	8.39
Cr	145	93	85	52	17		6	12
V	270	136	275	244	235		103	190
Ni	39	28	43	19	17		11	11
Co	56	19	39	25	44		12	28
Sc	tr	26	tr	16	45		17	43
Zr	87	47	124	455	270		35	52
Sr	280	240	200	695	335		190	215
Ba	475	500	335	365	625		305	425

I Lockatong argillite, New Jersey
J ditto
K ditto
L Yachats basaltic sandstone, Oregon
M Mafic graywacke, Washington
N ditto , Mt. Diablo, California (Clark, 1924)
O Graywacke, Limerick Township, Ontario
P ditto

TABLE 7 (continued)

	Q	R	S	T	U	V	W	X	Y	Z
SiO_2	58.61	32.21	32.88	50.20	50.00	50.83	45.61	47.65	50.11	51.61
TiO_2	1.00	0.01	0.49	0.75	0.82	1.10	2.67	4.02	1.86	2.01
Al_2O_3	13.81	0.90	9.04	13.80	18.84	18.64	15.55	14.49	16.01	17.70
Fe_2O_3	1.41	0.38	0.77	1.18	2.57	2.84	4.00	7.92	10.02	6.13
FeO	8.53	3.78	3.48	5.31	5.51	5.97	11.76	5.97	3.10	4.97
MnO	0.14	0.38			0.08	0.10	0.29	0.13	0.21	0.14
MgO	3.50	10.68	4.18	6.38	4.63	4.90	10.17	8.70	9.82	7.03
CaO	3.55	31.54	30.90	17.71	10.65	7.50	6.23	6.51	4.67	6.62
Na_2O	3.22	0.12	1.17	1.79	4.46	4.22	1.51	2.26	2.85	2.81
K_2O	3.34	0.02	0.85	1.30	1.18	1.83	1.95	2.01	1.45	1.01
P_2O_5	0.40	0.01					0.24	0.52	0.10	0.26
CO_2	0.93	19.69	15.20		0.10	0.11	0.13			
Cr	tr	tr					210	53	182	270
V	210	75					125	420	300	190
Ni	12	5					24	48	51	124
Co	33	tr					33	53	38	42
Sc	tr	n.d.					59	68	tr	34
Zr	195	15					151	140	30	165
Sr	130	115					230	390	140	785
Ba	595	tr					635	420	230	430

Q Graywacke, Limerick Township, Ontario
R Metasomatized limestone, Madoc Township, Ontario
S ditto , Glamorgan Township, Ontario (Adams, 1909)
T ditto recalculated without $CaCO_3$
U ditto
V ditto
W Tuff, Oregon
X ditto
Y ditto
Z Tuff, La Honda, California

DISCRIMINANT FUNCTION ANALYSIS THEORY

The discriminant function is a multivariate classifying function introduced by R.A. Fisher (1936) that permits an individual, on the basis of measurements of its characteristics, to be assigned to one of several groups. In two or more sets of individuals, that linear function of the several characteristics is determined which will distinguish most clearly between the groups. It is necessary that the groups to which individuals are to be assigned be pre-determined, so that the discriminant function can be computed using individuals whose classification is known; unknowns may then be classified by using the discriminant function. The function is especially useful is that a linear combination of several variables yields a single transformed variate.

The discriminant function is discussed in detail by Rao (1952, pp. 236-378), Kendall (1957, pp. 111-116, 144-170), and Williams (1959, pp. 175-194). In recent years there have been some applications of discriminant function analysis to geological problems (Griffiths, 1957; Potter et al., 1963; Middleton, 1962). An application to amphibolites was made by Kudo (1962).

Explanation of Statistical Procedures

In a multivariate population, p variables (x_1, x_2, ..., x_i, ..., x_p) are measured on each of n individuals making up the sample. If there are two populations, then two multivariate populations (k = 2) composed of n_1 and n_2 individuals respectively, result. The multivariate analogue of the

sample variance is the covariance (dispersion) matrix. The covariance matrix is obtained by dividing the SSP matrix by the appropriate number of degrees of freedom. The covariance matrix is made up of elements, w_{ij}, such that the diagonal element, w_{ii} is the variance of the ith variate, and the off-diagonal element w_{ij} $(i \neq j)$ is the covariance of the variates i and j. Thus the covariance matrices for any two multivariate populations whose variables have the same variances and covariances are identical. An analysis of variance (dispersion) may be performed where the covariance matrix is split into the between groups and within groups covariance matrices.

The discriminant function for a particular set of data is estimated as that function for which the ratio of the sums of squares and products between groups to within groups is a maximum. The computational procedures for discriminant functions are outlined by Rao (1952, pp. 247-248, 287-289) and Kendall (1957, pp. 146-147).

In this study two groups are used for classification, so the following discussion is limited to the two group case. In computing a discriminant function it is assumed that the two populations are multivariate normal with means $u_{11}, \ldots, u_{1p}$ and $u_{21}, \ldots, u_{2p}$ (as estimated by $\bar{x}_{1j}$ and $\bar{x}_{2j}$ for the first and second groups respectively and with identical covariance matrices w_{ij}. The logarithm of the likelihood ratio is:

$$\sum_{i,j=1}^{p} w^{ij} (u_{1j} - u_{2j}) x_i - \tfrac{1}{2} w^{ij} (u_{1i}u_{1j} - u_{2i}u_{2j})$$

where the matrix w^{ij} is the reciprocal of w_{ij} and x_i is the ith variable measured on each of n individuals of the population. According to Kendall (1957, p. 146): "The second part of this expression is a constant and without losing generality we can take as our function",

$$\sum_{i,j=1}^{p} w^{ij} (u_{1j} - u_{2j}) x_i .$$

When the estimators are inserted, the resulting discriminant function is

$$x = \sum_{i,j=1}^{p} w^{ij} (\bar{x}_{1j} - \bar{x}_{2j}) x_i .$$

Mahalanobis' Generalized Distance, D^2 can be used to measure the degree of overlap between any two multivariate populations in p-dimensional space. The basic equation for D^2 is given by Rao (1952, p. 246) as

$$D^2 = \sum_{i,j=1}^{p} w^{ij} d_i d_j ,$$

where $d_i = \bar{x}_{1i} - \bar{x}_{2i}$ and $d_j = \bar{x}_{1j} - \bar{x}_{2j}$.

By using the discriminant function, regions in p-dimensional space are separated by a hyperplane with the above equation for a suitably determined constant. An individual for which the value of the left-hand function, x, exceeds the constant value chosen is assigned to the first group and when it is less it is assigned to the second group.

An individual is assigned to one of the k-groups according to which of the x's is greatest when the measurements of the variables of the individual are substituted in each of the k equations. This is applicable for k equal to two groups, but for this case one equation is sufficient. In this study two discriminant functions were computed which were combined in one equation. Although this may be erroneous, the a priori possibilities of an individual belonging to one or the other group were assumed equal.

If the value of x is positive for an individual, it is classified with the first group (ortho-amphibolite), and if x is negative, the individual is assigned to the second group (para-amphibolite).

Tests of hypotheses

All the tests are based on the null hypothesis of variance ratios.

The hypothesis of equal means between two multivariate populations given that the covariance matrices are equal is tested by the statistic

$$\frac{n_1 n_2 (n_1 + n_2 - p - 1).D^2}{p(n_1 + n_2)(n_1 + n_2 - 2)} .$$

This test may be used as a variance ratio with $(n_1 + n_2 - p - 1)$ and p degrees of freedom (Rao, 1952, pp. 246-247).

The contribution of each variable i to the measure of the total separation of the two groups is given by $m_i d_i$ in the equation,

$$D^2 = m_1 d_1 + \ldots + m_i d_i + \ldots + m_p d_p .$$

Those values contributing most to the discrimination can easily be determined by inspection.

The variance of x is given by D^2, which is also equal to $\bar{x}_1 - \bar{x}_2$, therefore D is a measure of the standard deviation of x and the relationships

$$\frac{\frac{1}{2} D^2}{D} = \frac{1}{2}D$$

provides a measure of the probability of misclassification (p) of a single individual. The discriminant function is assumed to be normally distributed for each group. The value $\frac{1}{2}D^2/D$ is the ratio of the deviation from

the mean to the standard deviation and is equal to the standardized normal deviate, Z (Dixon and Massey, 1957, p. 52 and Table A-4), so the area corresponding to $\frac{1}{2}D$ gives the probability of misclassification.

Among the assumptions made in discriminant function analysis are the following:

1. the populations are multivariate normal,
2. the populations have identical covariance, dispersion matrices,
3. the discriminant functions are normally distributed in a particular group with equal variances,
4. the *a priori* probabilities that any item belongs to any group are equal, and
5. individuals of unknown character must belong to one or the other of the *a priori* groups and cannot belong to an undefined group.

Assumption (1) is not valid as the distributions are skewed both in arithmetic and logarithmic plots of the data. Assumption (2) has not been tested but is probably invalid as explained by Middleton (1962, p. 124). He states that normal distributions and identical covariance matrices are the exception rather than the rule in practice and that heterogeneity of covariances will weaken the discrimination only when great. Assumption (3) is probably invalid as the populations do not fit these requirements. Assumption (4) is probably approximately correct. A survey of the literature indicates that ortho- and para-amphibolites are reported in approximately equal abundances. Assumption (5) is difficult to evaluate because the metasomatically derived amphibolites must be considered. These are difficult, if not impossible to separate from ortho- and para-amphibolites as these two types may be to a greater or lesser degree metasomatic.

Use of a discriminant function in problems such as the classification of amphibolites with a group of trace elements has several advantages. As pointed out by Potter et al. (1963, p. 677),

> "One advantage is that an unknown individual can be assigned to one of several groups on the basis of a linear combination representing all k variables rather than attempting to classify the individual by the separate outcomes of each of the k variables. The latter procedure gives each variable the same weight in the discrimination when in reality the variables contribute unequally. A weighted linear combination also avoids complications that might develop in evaluating individual samples ..., e.g. having three out of six trace elements indicate one origin and the remaining three the opposite origin."

Further, they state (ibid, p. 678),

> "The discriminant function also provides a multivariate test of the difference between the two control groups. In addition it permits testing of different linear combinations of the discriminatory elements so that the best linear combination can be identified and subsequently used in classifying unknown samples."

STATISTICAL ANALYSIS AND RESULTS

One objective of this study was to determine whether a single discriminant function could serve to classify amphibolites from many localities. In order to do this, samples from several localities were used in calculation of the discriminant function. A listing of the samples used in trace element statistical calculations is in table 8.

Means, correlation matrices, and discriminant functions were calculated for each group of amphibolites. The computations for correlation matrices and discriminant functions were performed on a Bendix G15D digital computer using programs written by G.V. Middleton. In the statistical calculations on trace element data, one-half and one-tenth of the sensitivity limit values were used for "tr" and "n.d." respectively.

The nature of the distributions of trace elements in the two amphibolite groups has not been established. With small sample sizes as in this study, it is difficult to assess whether the distribution is normal or lognormal. Therefore discriminant functions were calculated for both arithmetic and logarithmically transformed data to determine which was best to use in this case. As may be seen in table 12, X_A, calculated on arithmetic data is expected to give superior discrimination and classification to X_{log}, for logarithmic transformation of data. Hence only arithmetic data has been retained.

The arithmetic and geometric means and the ranges for the eight trace elements in each group are listed in table 9. Except for Sr and Ba,

the arithmetic means of elements in the 16 ortho-amphibolites are greater than in the 16 para-amphibolites. Of the eight elements, Cr, Ni, Co, and Sc appear to be most different in the two groups and may be expected to provide good discrimination. The mean values for most trace elements in the Beartooth amphibolites are considerably higher than those of the other amphibolites studied. These values suggest that Cr, V, Co, Ba, and Sr might be good discriminators for this group of rocks, which is treated separately in the following.

Plots of the abundance values of the elements in the rocks used for calculating the discriminant functions (figures 4 and 5, after Faust et al., 1956) show that considerable overlap occurs between both amphibolite groups for all elements so that single-element comparisons are not likely to be very reliable for distinguishing amphibolites.

The more powerful multivariate methods appear to be suitable in attempting to effectively utilize the data.

Correlation matrices of the form

$$v = (r_{ii})$$

where $r_{ii} = 1.00$ and $i = 1, 2, \ldots, p$ were obtained from the covariance (dispersion) matrices as

$$ij = w_{ij} \Big/ (w_{ii} \cdot w_{jj})^{\frac{1}{2}},$$

TABLE 8

Samples Used to calculated means, correlation matrices,

and discriminant functions

16 ortho- and 16 para-amphibolites, Discriminant Functions x_A, x_B, x_{log}

ortho-amphibolite group	para-amphibolite group
Kirkland Lake - 1	Limerick - 4
- 2	- 7
Hamburg - 1	- 9
- 2	Detlor - 12
- 3	Kaladar
Metagabbro - 1	Yachats
- 2	SR 64-24
Hawaii Basalt Sand	Chandos 68-74-16
Broken Hill - 44	69-27-2
Packsaddle Schist L-13	69-32-1
L-14	Packsaddle Schist L-10
Beartooth RH 153-55	L-12
RDB-42B	Beartooth PA-21
RDB-135	PA-23
Chandos 69-30-2	92-55
69-35-7	Lockatong - 2

Beartooth Mountains, 8 ortho- and 8 para-amphibolites, Discriminant Function x_C

ortho-amphibolite group	para-amphibolite group
RDB - 42B	PA - 16
- 47	- 17
- 56	- 19
- 135	- 21
- 218	- 22
- 238	- 23
- 265	PAQ - 1
RH 153-55	DE 227-54

TABLE 9

Means and Ranges for Trace Element Abundances

	16 ortho-amphibolites			16 para-amphibolites		
	Mean	Geometric Mean	Range	Mean	Geometric Mean	Range
Cr	328	259	32-990	118	54	5-435
V	319	295	172-585	220	201	103-520
Ni	97	75	30-190	41	24	8-147
Co	52	57	29-118	32	29	12-56
Sc	54	48	10-115	38	35	16-73
Zr	185	100	41-610	183	87	35-455
Sr	235	215	100-465	252	226	90-695
Ba	232	170	35-780	304	226	37-625

	8 Beartooth ortho-amphibolites		8 Beartooth para-amphibolites	
	Mean	Range	Mean	Range
Cr	320	50-990	493	135-1500
V	200	140-315	314	155-505
Ni	104	48-160	100	48-173
Co	38	29-57	57	20-187
Sc	51	27-103	59	18-112
Zr	108	43-195	112	45-325
Sr	369	210-520	129	tr. -365
Ba	436	175-780	226	62-640

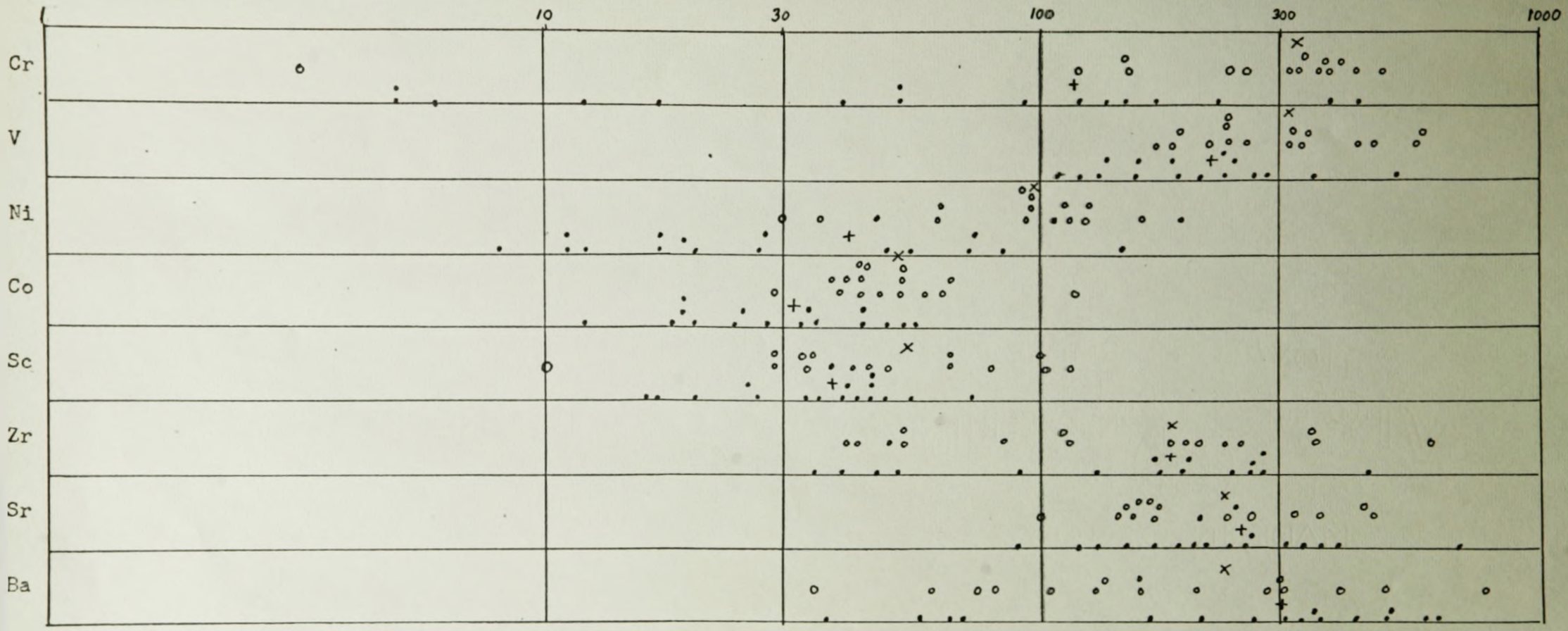


Figure 4. Abundance diagram of trace elements for rocks used in calculation of discriminant functions, X_a, X_b, and X_{log}.

° Ortho-amphibolites, × mean
· Para-amphibolites, + mean

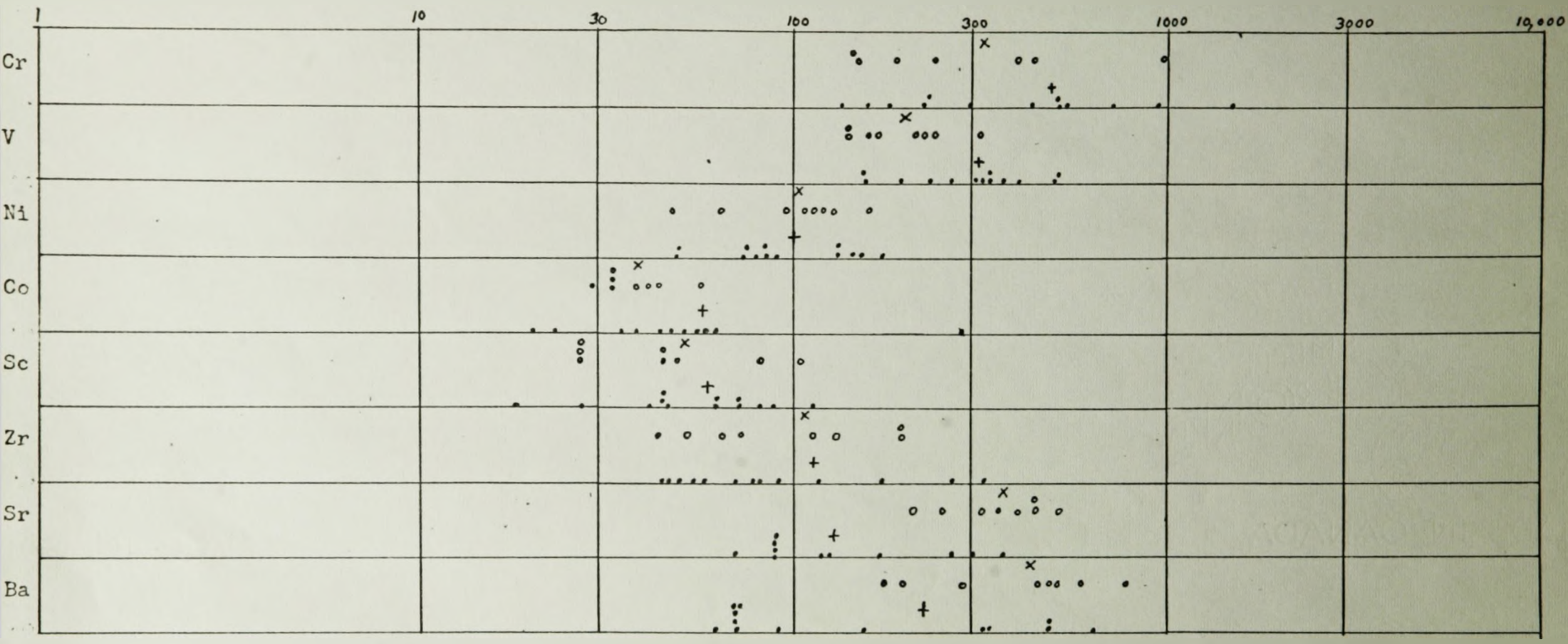


Figure 5. Abundance diagram of trace elements in rocks used in calculation of discriminant function, X_c.

o Ortho-amphibolites, X mean
• Para-amphibolites, + mean

where w_{ij} are the elements of the convariance matrix. The correlation matrices are in tables 10 and 11. The significant correlations are diagrammatically represented in figures 6 and 7 using the method of Chave and Mackenzie (1961).

Correlations of Cr, Ni, Co, and V in ortho-amphibolites may reflect the tendencies of these elements to associate with femic major components in igneous rocks (Rankama and Sahama, 1950, p. 512, 595-597, 681-682). Sc is correlated in a similar fashion and presumably also because of association with femic major components in para-amphibolites. The correlation between Ba and Sr in amphibolites suggests that they have similar geochemical behavior in these rocks. In the para-amphibolites, Sr and Zr are strongly correlated; this may be interpreted as meaning that both behave in similar ways in these rocks and may both be concentrated in amphiboles and biotites.

TABLE 10

Correlation matrix, 16 pA, Arithmetic Data, Trace elements

	Cr	V	Ni	Co	Sc	Zr	Sr	Ba
Cr	1.000	0.047	0.759	0.118	0.482	-0.180	-0.009	-0.175
V		1.000	0.299	0.802	0.487	0.300	-0.172	0.524
Ni			1.000	0.451	0.577	-0.253	-0.222	-0.494
Co				1.000	0.664	0.094	-0.301	-0.481
Sc					1.000	-0.117	-0.211	-0.455
Zr						1.000	0.610	-0.083
Sr							1.000	0.293
Ba								1.000

Correlation matrix, 16 oA, Arithmetic Data

	Cr	V	Ni	Co	Sc	Zr	Sr	Ba
Cr	1.000	0.025	0.470	-0.191	0.178	-0.592	-0.200	-0.064
V		1.000	0.293	0.484	0.267	0.042	-0.398	-0.490
Ni			1.000	-0.176	0.506	-0.140	-0.077	0.032
Co				1.000	-0.328	0.060	-0.174	-0.243
Sc					1.000	0.308	-0.088	-0.229
Zr						1.000	0.295	-0.023
Sr							1.000	0.399
Ba								1.000

At the 95% level of significance, correlation coefficients greater than ± 0.482 are significant.

TABLE 11

Beartooth Amphibolites

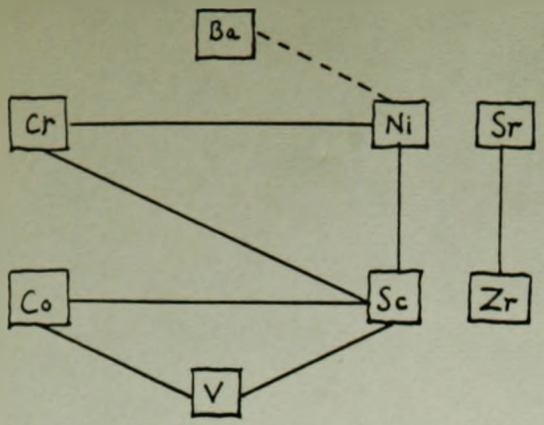
Correlation Matrix, 8 pA, Arithmetic Data

	Cr	V	Ni	Co	Sc	Zr	Sr	Ba
Cr	1.000	0.491	0.142	-0.246	0.687	-0.484	-0.384	-0.464
V		1.000	0.794	0.136	0.755	-0.712	-0.801	-0.643
Ni			1.000	0.358	0.346	-0.387	-0.504	-0.328
Co				1.000	-0.245	-0.231	-0.080	0.066
Sc					1.000	-0.460	-0.486	-0.409
Zr						1.000	0.895	0.936
Sr							1.000	0.890
Ba								1.000

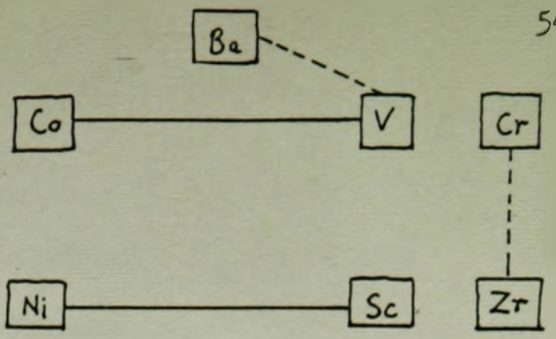
Correlation Matrix, 8 oA, Arithmetic Data

	Cr	V	Ni	Co	Sc	Zr	Sr	Ba
Cr	1.000	0.667	0.716	0.090	0.646	-0.095	-0.392	-0.085
V		1.000	0.858	0.615	0.837	-0.106	-0.847	0.246
Ni			1.000	0.646	0.866	0.123	-0.855	0.343
Co				1.000	0.761	-0.217	-0.909	0.257
Sc					1.000	-0.308	-0.887	0.003
Zr						1.000	0.037	0.759
Sr							1.000	-0.355
Ba								1.000

At the 95% level of significance, correlation coefficients greater than ±0.666 are significant.

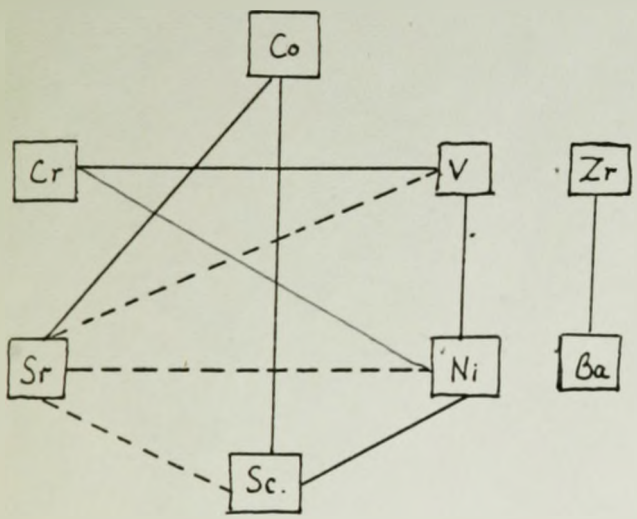


16 pA

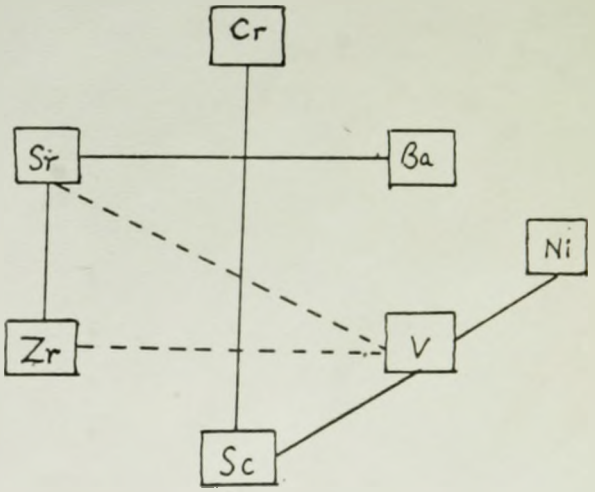


16 oA

Figure 6. Correlation diagrams for 16 para- and 16 ortho-amphibolites
Positive correlations indicated by solid lines; negative correlations by broken lines.



8 oA



8 pA

Figure 7. Correlation diagrams for 8 ortho- and 8 para-amphibolites from the Beartooth Mountains.
Positve correlations indicated by solid lines; negative correlations by broken lines.

Discriminant Function Analysis Results

Trace Elements

The apparently successful application of the discriminant function to amphibolite classification by Kudo (1962) was the basis for further work along similar lines in this study. The influence of geochemical provinces has been considered in attempting to calculate a universally applicable discriminant function for amphibolite classification.

Geochemical provinces may be partially defined on geological and geographical grounds but are largely defined by differences in the relative abundances of particular elements in given rock types in different regions. Such provincial differences have been shown for Zr (Chao and Fleischer, 1960), Sc (Fryklund and Fleischer, 1963), and Sr (Turekian and Kulp, 1956) in igneous rocks. During this study, it soon became apparent that the trace-element complexion of amphibolites varies from one locality to another. For example, ortho- and para-amphibolites from the Beartooth Mountains contain, on the average, different amounts of V, Ni, Sr, and Ba than the other amphibolites studied. In the Beartooth para-amphibolites, Cr and Ni, are, on the average, in greater abundance than in ortho- and para-amphibolites from other localities.

Such differences in element abundances complicate the distinction of amphibolite types by discriminant function analysis since the abundance values of a particular element overlap greatly between ortho- and para-amphibolites. Elements which consistently have different relative abundances in the two groups and which have minimum overlapping between groups make the best discriminators.

In this study the discriminant functions calculated by Kudo (1962) were used originally to attempt classification of samples used by the author. It soon became obvious that the two functions for trace elements would be of little use because of the high incidence of misclassification of samples of known origin. The errors in classification may have been due to differences in analytical results compared to Kudo's results and to provincial differences in the chemistry of the amphibolites.

It was deemed necessary to calculate new discriminant functions in order to obtain better classification results. This was done (see table 12) using a Bendix G15D computer and programs written by G.V. Middleton (User's Project No. 695). Eight trace elements, Cr, V, Ni, Co, Sc, Zr, Sr, and Ba were used as was done by Kudo. The samples used in calculation of the functions are listed in table 8. Functions for arithmetic and logarithmic data were calculated. The best two discriminators are Co and Ni and a separate function was calculated using only these two variates. Variance-ratio tests (Rao, p. 247) show that the discrimination is effective at the 95% level of significance (table 12) for the functions calculated on arithmetic data but not for the function calculated on logarithmic data.

Of the 32 samples used to compute the discriminant functions, x_A, x_B, and x_{log}, 4 (12.5%) were misclassified by the 8-element arithmetic function, 7 (22%) were misclassified by the 8-element logarithmic function and 5 (15.6%) were misclassified by the arithmetic 2-element function. These are different from the theoretical probabilities of misclassification, P, of 2.0% and 16.2% respectively for the 8-element and 2-element arithmetic functions. P is figured from the equation,

$\frac{\frac{1}{2}D^2}{D} = \frac{1}{2}D$ where $\frac{1}{2}D$ is the limit of overlap of groups and therefore where misclassification may occur.

When a total of 52 rocks of known origin was used the misclassification was 9.4% using both 8 and 2 element functions (tables 13 and 14). Among those rocks correctly classified using other workers' analyses (uncorrected trace element values because no means of interlaboratory comparison was available) are basalts from six basaltic provinces of the United States analyzed by Bartel et al. (1963); three glaucophane schists from California (Coleman and Lee, 1963); a graywacke (Pettijohn, 1963) and the "average" shale, carbonate, and basalt of Turekian and Wedepohl (1961). The standard diabase, W-1 was incorrectly classified using both the recommended values (Fleischer and Stevens, 1963) and the values obtained in this study (table 12). All of the sedimentary rocks analyzed in this investigation were correctly classified. Three of four tuffs were classified with the para-amphibolites.

The 8 element function, x_A, was used to classify amphibolites of uncertain origin from several localities. The Connemara amphibolites were studied by Evans and Leake (1960) who concluded that the rocks are probably of igneous origin, being "... intrusions, lavas, or tuffs of sodic basalt composition". Six samples of these rocks were analyzed and five were classified as of meta-sedimentary origin and one of meta-igneous origin. These results appear to be consistent with the data (i.e. low Cr and Ni in some specimens) which appear more akin to sedimentary rocks than igneous works. They could represent tuffs with sedimentary characteristics as the Oregon tuffs analyzed in this study.

Four amphibolites from the N.W. Adirondacks supplied by A.E.J. Engel were classified as of meta-sedimentary origin. No conclusions on their origin have been reached by Engel (1962, pp. 76-78), but Leake (1963) concludes that they are of igneous origin on somewhat dubious grounds (see section on Niggli No. plots).

The Packsaddle Schist of Texas is an amphibolite investigated by Billings (1962). Both banded amphibolites with bands from several millimeters to several centimeters thick within meta-sedimentary gneisses and thick, massive amphibolites occur in this group. Billings (ibid) concluded that the banded amphibolites were probably formed from tuff-sediment mixtures and the massive amphibolites are meta-igneous rocks. The results of the writer's work classify some of each group of individuals as para-amphibolites and some as ortho-amphibolites.

Amphibolites from Broken Hill, Australia were also studied and classified. A metagabbro in the group was correctly classified. The other nine amphibolites are of undetermined origin and some were classified as para-amphibolites and others as ortho-amphibolites. Binns (1962) rejects a sedimentary or metasomatic origin for the rocks and favors an igneous parentage.

A metasomatized limestone from Madoc Township, Ontario was classified as a para-amphibolite. The rock is partially "amphibolitized" and is analogous to rocks described by Adams (1909) and Adams and Barlow (1910) from Glamorgan Township, Ontario.

Beartooth Mountains Amphibolites

Neither of the two discriminant functions employed in classification gave good results with rocks of known origin from the Beartooth Mountains. This is a reflection of the great differences in the trace element chemistry of that province. An eight-element function, x_c (table 12), computed using 8 para- and 8-ortho-amphibolites from the Beartooth group was fairly successful in classifying Beartooth rocks of known origin. Four of 21 (19%) samples were misclassified. The theoretical value, P, is less than 0.5%. A variance-ratio test indicates significant discrimination at the 95% level (table 12). The two best individual discriminators in this group are Ni and V. Classification results for this group are in table 14.

Major Elements

Major elements were successfully used by Kudo in a discriminant function to distinguish between ortho- and para-amphibolites. Consideration of the means of the two groups of amphibolites, the variation of concentration of major elements, and the great overlapping of the two groups with regard to major element chemical composition has led the author to conclude that discriminant function analysis on major elements is unlikely to be significant. Ti, which has been suggested as being of use in distinguishing ortho- from para-amphibolites by Lapadu-Hargues (1958) is clearly not useful. Examples of para-amphibolites with greater than 0.8% TiO_2 (the limiting value for pA according to Lapadu-Hargues) are Limerick No. 9, Detlor, No. 12, Kaladar, PA-17, PA-21, and 69-32-1. Some ortho-amphibolites have less than 0.8% TiO_2 including 153-55, RDB-47, RDB-56, and RDB-135. Other elements display such overlapping of concentrations also.

TABLE 12

Discriminant Functions

X_A = 0.0282 Cr - 0.0117 V + 0.0840 Ni + 0.3642 Co + 0.0267 Sc + 0.0193 Zr - 0.0011 Sr + 0.0064 Ba - 30.5558

D^2 = 16.95 P = 2.0% F = 12.99

X_{log} = 0.271 log Cr - 0.982 log V + 1.841 log Ni + 4.837 log Co + 0.564 log Sc - 0.416 log Zr + 0.366 log Sr + 0.800 log Ba - 12.267

D^2 = 2.025 P = 24.% F = 0.26

X_B = 0.0363 Ni + 0.0754 Co - 5.8083

D^2 = 3.83 P = 16.2% F = 2.94

X_C = - 0.0090 Cr - 0.3807 V + 0.5501 Ni - 0.0601 Co + 0.2774 Sc + 0.0130 Zr + 0.1862 Sr + 0.1249 Ba - 15.5675

D^2 = 125.35 P = 0.01% F = 31.45

X_D = 0.928 TiO_2 + 1.478 Fe_2O_3 - 0.168 FeO + 0.164 MgO + 0.126 CaO + 1.002 P_2O_5 - 4.184

D^2 = 4.18 P = 11.5% F = 13.04

TABLE 13

Classification of Amphibolites and Some Other Rocks of Known Origin

using 8 trace elements

		Origin	X_A	Classification
Average of 16 pA		meta-sedimentary	-8.35	sedimentary
Average of 16 eA		meta-igneous	5.85	igneous
Basalt	) Turekian	igneous	2.37	igneous
Shale	) &	sedimentary	-10.36	sedimentary
Carbonate	) Wedepohl	sedimentary	-30.32	sedimentary
Graywacke	Pettijohn	sedimentary	-23.50	sedimentary
Lockatong Argillite				
1		sedimentary	-1.28	sedimentary
2		sedimentary	-15.72	sedimentary
3		sedimentary	-8.98	sedimentary
W-1 (Diabase)		igneous	-2.21	sedimentary
Basalts				
Mt. Lassen, Calif.		igneous	15.61	igneous
Farmington, Conn.		igneous	0.77	igneous
Kilauea, Hawaii		igneous	8.81	igneous
Dietrich, Idaho		igneous	6.08	igneous
Jemez Mtns., N.M.		igneous	14.85	igneous
Johnnycake Mt., Ore.		igneous	2.68	igneous

TABLE 14

Classification of Amphibolites by

Discriminant Functions X_A and X_B

Sample	Origin from Geological Evidence	Classification by Discriminant Function X_A	X_A	X_B
Kirkland Lake - 1	igneous	igneous	2.05	0.85
- 2	"	"	10.47	2.16
Hamburg - 1	"	sediment	-3.27	-1.78
- 2	"	igneous	12.92	2.01
- 3	"	"	3.46	-0.58
Metagabbro - 1	"	"	7.45	0.72
- 2	"	"	22.69	5.34
Hawaii Sand	"	"	10.53	2.62
Broken Hill - 44	"	"	2.26	1.07
Packsaddle Schist L-13	"	"	11.73	2.74
L-14	"	"	3.00	1.53
Beartooth RH 153-55	"	"	1.76	1.39
RDB - 42B	"	"	5.86	0.94
-135	"	"	27.85	3.24
Chandos 69-30-2	"	sediment	-0.78	-1.33
69-35-7	"	igneous	16.55	5.08
Limerick - 4	sedimentary	sediment	-22.60	-4.50
- 7	"	"	-16.68	-3.30
- 9	"	"	-11.84	-2.88
Detlor - 12	"	"	-5.65	-1.09
Kaladar	"	"	-9.36	-3.02
SR 64.24	"	"	-5.33	-1.87
Yachats	"	"	-10.89	-3.23
Chandos 68-74-16	"	"	-4.52	-0.12
69-27-2	"	"	-8.95	-1.84
69-32-1	"	"	-13.91	-3.76
Packsaddle Schist L-10	"	"	-14.31	-2.95
L-12	"	igneous	12.47	3.35
Beartooth PA-21	"	"	0.26	-0.48
PA-23	"	sediment	-3.95	0.56
92-55	"	"	-1.55	-2.52
Lockatong - 2	"	"	-15.72	-3.36

Above samples were used to compute discriminant functions X_A and X_B

TABLE 14 (continued)

Sample	Origin from Geological Evidence	Classification by Discriminant Function X_A	X_A	X_B
JCC - 1	sediment	sedimentary	-3.78	-2.45
- 2	"	"	-3.65	-0.07
- 3	"	"	-8.62	-1.09
- 4	igneous	igneous	+1.60	+0.62
Hibernia - 1	meta-sediment	sedimentary	-5.30	-2.29
- 2	"	"	-4.91	-2.55
- 3	"	"	-12.08	-3.03
Lockatong - 1	sediment	sedimentary	-1.28	-0.17
- 2	"	"	-8.98	-1.31
Madoc	metasomatic	"	-28.77	-5.25
Broken Hill - 1	unknown	"	-6.69	-0.48
- 3	"	igneous	+6.86	-3.11
- 9	"	sedimentary	-7.07	-0.50
- 12	"	igneous	+0.08	1.76
- 13	"	sedimentary	-3.85	2.48
- 14	"	"	-4.00	-0.22
- 28	"	igneous	6.28	3.10
- 29	"	sedimentary	-6.29	0.16
- 37	"	"	-0.31	1.07
Packsaddle Schist - L 4	unknown	igneous	10.94	2.85
- L 5	"	"	4.22	2.00
- L 8	"	"	15.08	4.47
- L15	"	"	11.13	3.10
- L16	"	sedimentary	-4.44	-0.81
- LW-2	"	igneous	17.99	2.06
- HC-2	"	sedimentary	-2.84	-0.03
- HC-13	"	igneous	4.78	2.30
- HC-15	"	sedimentary	-0.96	1.16
- HC-16	"	"	-6.71	-0.77

TABLE 14 (continued)

Sample		Origin from Geological Evidence	Classification by Discriminant Function X_A	X_A	X_B
Connemara	- 165	unknown	sedimentary	-16.50	-2.78
	- 360	"	"	-6.99	-1.26
	- 522	"	"	-0.67	+0.36
	-2506	"	"	-10.96	-3.56
	-2515	"	igneous	+7.40	+1.25
	-2522	"	sedimentary	-16.34	-2.67
	-2518	"	"	-4.94	-1.09
	- 194	"	"	-6.09	-0.83
	- 763A	"	igneous	13.70	5.43
	-2516	"	"	57.52	15.07
Adirondacks	- A 8	"	sedimentary	-0.02	2.24
	- A16	"	"	-3.79	-0.12
	- A17	"	"	-7.50	+0.14
	- A326	"	"	-8.19	-0.21
Chandos Township	69-30-6	igneous	igneous	10.59	-0.53
	69-34-7	"	"	20.59	-0.62
	69-28-5	"	sedimentary	-15.40	-3.65
	69-28-2	"	"	-8.00	-3.04
	68-78-1	sedimentary	"	-10.96	-3.65
	70-146-6	"	"	-23.53	-4.49
	70-139-1	"	"	-25.70	-4.63
Cazadero Area, Coleman & Lee					
	16-CZ-59	sedimentary	"	-20.44	-2.15
	SFS-131	igneous	"	+62.21	24.88
	SFS-192	"	"	+4.66	6.20

TABLE 14 (continued)

Classification of Beartooth Mountains Amphibolites by Discriminant Function X_C

Sample	Origin from Geological Evidence	Classification by Discriminant Function	X_C
PA - 16*	meta-sediment	sediment	-53.17
17*	"	"	-18.42
19*	"	"	-58.59
21*	"	igneous	40.28
22*	"	sediment	-23.75
23*	"	"	-40.31
PAQ-1*	"	"	-24.83
DE 41-53	"	"	-58.00
227-54*	"	"	-57.31
125-53	"	igneous	22.30
131-54	"	sediment	-112.34
Z-5	"	igneous	117.71
92-55	"	"	90.05
RDB-42B*	meta-igneous	igneous	120.23
56 *	"	"	76.63
135 *	"	"	52.31
218 *	"	"	89.99
238 *	"	"	138.03
265 *	"	"	126.87
RH 153-55*	"	"	103.17
RDB-47 *	"	"	84.82
RDB-80A	unknown	igneous	109.63
284	"	"	195.93
236	"	sediment	-33.66
Z-8	"	igneous	72.42

* Samples used in calculation of discriminant function, X_C

Correlation matrices were calculated for 40 ortho- and 40 para-amphibolites listed in table 15, using TiO_2, P_2O_5, FeO, Fe_2O_3, MgO, and CaO. The correlation matrices are in table 16.

Correlations of Mg, Ca, Ti, and Fe-oxides in ortho-amphibolites probably result from their close association in mafic minerals. Ca and P-oxides are correlated and this can be traced to their association in apatite. The Mg, Fe, Ti, and P-oxides correlations in para-amphibolites are probably also due to their association in mafic minerals.

A function, X_D, was calculated by using data for the 40 ortho- and 40 para-amphibolites (5 metasomatic amphibolites from limestone included) listed in table 15. The oxides used in the calculations include, TiO_2, P_2O_5, Fe_2O_3, FeO, CaO, and MgO. The function is in table 12 and the variance-ratio test shows it to be significant at the 99.9% level. The theoretical probability of misclassification is about 11.5%. A total of 84 amphibolites of known origin were classified with misclassification occurring for 36% of the individuals. With these poor results, no classification of unknowns by major elements was attempted.

TABLE 15

Sources of Major Element Analyses for Correlation Matrices and Discriminant Function X_D

Ortho-amphibolites

Source	No. Analyses
Harris (1959)	1
Bentley (unpublished)	7
Simonen (1953)	8
Wilcox and Poldervaart (1958)	12
Engel (1956)	2
Binns (1962)	1
Kudo (1962)	6
This Study	3

Para-amphibolites

Source	No. Analyses
Eckelmann and Poldervaart (1957)	4
Bentley (unpublished)	7
Harris (1959)	2
Wilcox and Poldervaart (1958)	3
Adams and Barlow (1910)	2
Engel (1956)	4
Simonen (1953)	6
Kudo (1962)	6
This Study	5
Walton et al. (1964)	1

TABLE 16

Correlation Matrices, Major Elements

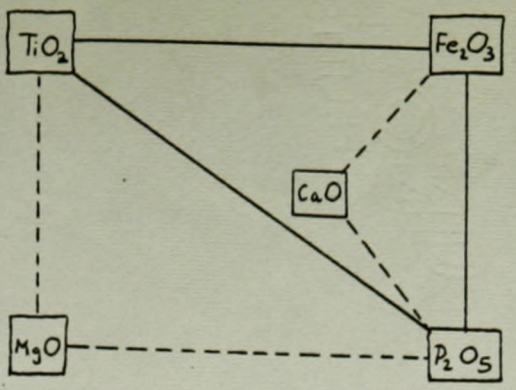
40 ortho-amphibolites

TiO_2	Fe_2O_3	FeO	MgO	CaO	P_2O_5	
1.000	0.321	0.725	-0.479	-0.269	0.475	TiO_2
	1.000	-0.069	-0.133	-0.441	0.428	Fe_2O_3
		1.000	-0.208	-0.041	0.119	FeO
			1.000	0.037	-0.412	MgO
				1.000	-0.465	CaO
					1.000	P_2O_5

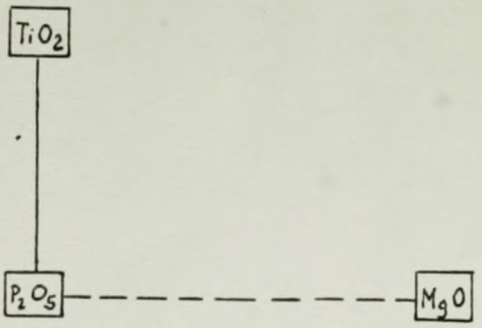
40 para-amphibolites

TiO_2	Fe_2O_3	FeO	MgO	CaO	P_2O_5	
1.000	0.096	0.408	-0.243	-0.017	0.447	TiO_2
	1.000	0.284	0.009	-0.122	-0.134	Fe_2O_3
		1.000	0.250	0.217	0.049	FeO
			1.000	0.226	-0.433	MgO
				1.000	-0.026	CaO
					1.000	P_2O_5

At the 95% level of significance, correlation coefficients greater than ±0.320 are significant.



Ortho-amphibolites



Para-amphibolites

Figure 8. Correlations between major element oxides in 40 ortho- and 40 para-amphibolites. Positive correlations indicated by solid lines; negative correlations by broken lines.

CONCLUSIONS

In this investigation it was attempted to answer several questions pertaining to amphibolites. They are:

1. Is it possible to use trace-element data transformed to a linear discriminant function to distinguish ortho- from para-amphibolites?

2. Are there any sediments with the composition of amphibolites and if so, how do they compare to para-amphibolites with regard to trace-element chemistry?

3. How do basaltic tuffs compare chemically to amphibolites?

4. Are provincial influences significant with respect to chemical variations in amphibolites?

Answers have been found to these questions although they are not absolute in all cases. It has been shown that discriminant function analysis can be successfully applied to amphibolite classification problems with limitations imposed by extreme variations in trace-element abundances as exemplified by the Beartooth amphibolites. A function which misclassifies 10% of the rocks classified is clearly a considerable improvement over the 50% chance of misclassification incurred in guessing.

There are sediments, chiefly of mafic graywacke type which are similar to amphibolites in composition. Although these may be derived from basic igneous rocks, their trace element chemistry is analogous to that of para-amphibolites. Some sodic argillaceous rocks are also more like amphibolites chemically than has been previously realized.

Basaltic tuffs are chemically similar to amphibolites; their trace-element chemistry may be considerably influenced by their environment of deposition and diagenetic processes. Therefore, tuffs may display minor element chemistry characteristic of igneous rocks or sediments.

Provincial influences are quite significant as regards chemical variation in amphibolites, especially with minor elements. Thus, the Beartooth Mountains amphibolites have extremely different trace-element abundances than the other amphibolites studied. Provincial differences reflect differences in parent magmas, the rocks from which sediments were derived, and diagenetic and metamorphic processes.

While it is possible to classify any amphibolite with the discriminant functions calculated, the results may be of questionable value in some cases. This will be true especially for amphibolites of unknown origin from an area where none of the amphibolites are of known origin so that there are no "knowns" to use as "standards" for comparison. It is therefore recommended that if possible, several analyses of amphibolites of known origin be used in discriminant function analysis of unknowns from a given area as was done by Kudo (1962). Even when such precautions are taken, misclassification is possible as is illustrated by the statistical results on the Beartooth rocks and the Chandos rocks (Kudo, 1962). The degree of misclassification will be less than when a general discriminant function is used as is again illustrated by the Beartooth rocks.

With this in mind, it may be understood that the classifications of the Connemara and Broken Hill amphibolites are less reliable than those of the Ontario, New Jersey, and Beartooth rocks.

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APPENDIX 1

Chemical Analyses

Ortho-amphibolites

	1	2	3	4	5	6	7	8
SiO_2	47.53	48.79	48.01	55.78	50.20	52.98	53.32	52.61
TiO_2	1.23	0.87	2.88	0.71	0.75	0.35	0.40	0.30
Al_2O_3	17.10	15.02	15.12	13.82	15.01	19.40	18.38	12.44
Fe_2O_3	1.80	2.03	1.53	2.20	2.41	1.77	2.02	1.92
FeO	7.02	9.28	13.55	6.38	6.48	4.60	4.68	7.12
MnO	0.23	0.20	0.21	0.14	0.14	0.10	0.10	0.15
MgO	4.85	7.09	5.73	7.13	9.27	6.52	7.38	15.38
CaO	14.17	9.90	7.42	6.77	9.56	9.41	9.62	7.29
Na_2O	3.27	2.52	3.16	2.56	2.62	3.10	2.77	1.66
K_2O	0.64	1.32	1.04	1.92	1.26	0.53	0.59	0.89
H_2O+	1.14	2.36	0.42	1.54	0.76	0.35	0.46	0.45
H_2O-	0.09	0.15	0.15	0.07	0.04	0.00	0.03	0.01
P_2O_5	0.13	0.06	0.40	0.23	0.45	0.04	0.05	0.10
CO_2	0.18	0.12	0.09		0.15	0.05	0.00	0.00
l.o.i.				2.23				
	99.38 a	99.71a	99.71a	99.28a	99.20b	99.20b	99.80b	100.32b
Cr	375*	485*	119*	148*	240*	50#	190#	990*
V	237	315	235	216	240	140	140	315
Ni	30	122	47	113	107	48	64	160
Co	39	47	64	41	38	29	33	43
Sc	33	38	35	49	45	27	27	103
Zr	53	53	360	112	195	52	65	43
Sr	156	265	240	355	320	520	450	250
Ba	160	310	395	495	780	195	175	285

Description and location of samples given in Appendix 2.

* Trace element analyses by P.C. van de Kamp (all elements).
\# Trace element values by conversion (see pp. 25-26). (all elements).
Major element analysts at end of this appendix.

	9	10	11	12	13	14	15	16
SiO_2	52.13	55.81	57.40	53.3	48.5	48.7	50.0	48.5
TiO_2	0.42	0.50	0.85	1.92	1.86	1.47	2.15	0.94
Al_2O_3	9.07	12.88	14.11	13.8	15.1	15.7	15.7	13.2
Fe_2O_3	3.49	2.71	4.89	3.0	2.2	1.8	5.5	0.72
FeO	7.34	6.19	4.90	12.10	10.46	9.53	5.23	4.83
MnO	0.18	0.14	0.13	0.29	0.19	0.18	0.11	0.07
MgO	13.96	8.67	6.83	3.6	7.1	6.8	3.6	3.8
CaO	10.86	8.65	5.68	6.6	9.5	10.4	7.0	16.8
Na_2O	0.99	2.30	2.85	3.44	2.84	2.69	3.67	2.75
K_2O	0.90	0.92	2.04	0.40	0.20	0.32	3.25	1.33
H_2O+	0.34	0.39	0.46	H_2O 0.97	1.19	1.19	0.82	0.73
H_2O-	0.01	0.00	0.01	loi.2.16	1.72	1.84	1.47	7.74
P_2O_5	0.26	0.24	0.37	0.43	0.16	0.09	1.48	0.34
CO_2	0.00	0.00	0.00	0.74	0.67	0.49	0.33	6.95
	99.90b	99.43b	100.52b	100.7a	100.0a	99.5a	98.8a	101.0a
Cr	150#	440#	400#	32#	340#	625#	3#	105#
V	225	168	160	172	435	315	248	180
Ni	128	120	96	63	190	47	64	20
Co	57	33	33	29	53	46	38	19
Sc	81	45	27	102	115	110	4	10
Zr	72	195	130	610	210	165	210	190
Sr	210	400	450	445	145	132	2450	1000
Ba	505	455	595	160	60	73	5200	605

	17	18	19	20	21	22	23	24
SiO_2	49.85	50.5	60.2	55.5	57.3	48.7	58.8	56.5
TiO_2	1.06	3.03	0.80	0.76	0.78	1.60	0.76	0.93
Al_2O_3	16.14	14.5	14.9	15.8	13.5	15.6	15.6	16.4
Fe_2O_3	3.05	3.0	0.76	2.1	0.75	3.3	0.88	2.9
FeO	8.33	13.85	5.72	4.55	3.43	8.74	5.69	4.30
MnO	0.19	0.32	0.02	0.07	0.05	0.20	0.04	0.15
MgO	7.36	2.6	4.6	4.3	3.4	5.4	4.5	2.9
CaO	12.14	6.3	5.4	10.1	13.1	10.3	5.8	7.5
Na_2O	1.87	4.58	4.29	2.04	2.64	3.76	5.31	4.88
K_2O	0.22	0.44	0.91	2.24	0.33	0.26	0.45	0.89
H_2O+	0.46	H_2O 0.88	0.34	0.63	0.69	1.19	1.22	1.10
H_2O-	0.06	loi.1.63	1.60	1.77	4.65	2.01	2.23	1.73
P_2O_5	0.02	1.31	0.13	0.22	0.21	0.15	0.19	0.27
CO_2		0.06	1.02	1.09	3.84	0.67	0.94	0.69
	100.75f	101.4a	99.1a	99.4a	100.0a	99.9a	100.2a	99.4a
Cr	315*	3#	174#	3#	1#	120#	170#	52#
V	345	24	320	160	163	520	154	121
Ni	96	12	20	28	13	55	72	17
Co	45	31	19	4	12	49	18	19
Sc	66	40	10	10	4	55	40	34
Zr	85	460	155	205	25	245	200	280
Sr	100	225	330	875	134	170	260	310
Ba	35	117	1730	275	129	37	210	355

	25	26	27	28	29	30	31	32
SiO_2	51.67	47.85	58.61	51.46	55.89	50.82	50.72	48.86
TiO_2	0.70	0.86	1.00	2.93	1.08	0.68	0.86	0.72
Al_2O_3	13.95	12.77	13.81	14.75	11.68	12.24	11.15	14.50
Fe_2O_3	1.55	0.81	1.41	2.30	3.69	2.99	2.96	2.84
FeO	6.24	6.29	8.53	10.54	4.64	9.86	9.43	8.78
MnO	0.12	0.10	0.14	0.12	0.11	0.20	0.26	0.14
MgO	8.93	3.67	3.50	5.00	5.61	10.34	11.03	9.20
CaO	9.89	13.85	3.55	6.47	10.44	10.96	10.26	12.39
Na_2O	3.51	2.72	3.22	4.59	2.49	1.37	2.25	2.15
K_2O	1.11	1.17	3.34	0.23	1.35	0.50	0.73	0.60
H_2O+	1.72	1.02	1.25	0.66	1.34	0.19	0.46	0.14
H_2O-	0.23	0.17	0.17	0.23	nil	0.00	0.00	0.02
P_2O_5	0.14	0.24	0.40	0.36	0.16	0.00	0.00	0.04
CO_2	0.13	8.39	0.93	0.41	1.56	0.00	0.15	0.00
	99.89a	99.91a	99.86a	100.05a	100.04c	100.15b	100.26b	100.38b

Cr	365*	12*	tr.*	40*	116*	950#	720#	540#
V	280	190	210	355	130	310	365	335
Ni	26	11	12	20	27	84	144	80
Co	34	28	33	53	24	55	61	47
Sc	47	43	tr.	49	36	72	63	81
Zr	63	52	195	280	130	45	81	46
Sr	190	215	130	120	150	90	90	90
Ba	220	425	595	57	265	70	91	70

	33	34	35	36	37	38	39	40
SiO_2	52.96	50.71	53.97	48.08	48.45	52.76	50.92	48.06
TiO_2	1.23	0.98	1.20	0.82	1.36	0.40	0.42	0.49
Al_2O_3	15.24	14.58	14.92	14.20	16.13	12.56	14.07	16.57
Fe_2O_3	2.49	3.63	3.06	1.52	1.24	1.86	2.23	1.83
FeO	7.17	8.71	8.06	10.15	10.47	7.10	9.96	9.32
MnO	0.16	0.23	0.20	0.24	0.24	0.27	0.15	0.18
MgO	5.19	7.04	6.29	10.04	7.82	10.79	7.96	8.06
CaO	7.69	10.39	9.52	11.42	10.30	8.14	9.62	9.38
Na_2O	3.46	2.81	2.08	2.37	1.56	2.61	2.09	3.32
K_2O	1.89	0.80	0.87	0.59	0.78	1.28	0.54	0.47
H_2O+	0.98	0.27	0.08	0.05	1.32	0.93	1.50	1.72
H_2O-	0.06	0.08	0.02	0.04	0.05	0.00	0.17	0.12
P_2O_5	0.61	0.08	0.18	0.06	0.11	0.04	0.02	0.12
CO_2	0.25	0.20	0.00	0.00	0.00	1.01	0.00	0.00
	99.38a	100.51b	100.45b	99.58b	99.83b	99.75b	99.65b	99.64b
Cr	225*	230#	135#	520#	158*	1500*	183*	510*
V	233	320	265	335	500	196	505	402
Ni	74	132	84	132	75	173	48	151
Co	35	187	44	38	63	51	59	57
Sc	46	45	27	72	63	45	112	89
Zr	265	70	91	78	118	48	58	54
Sr	270	120	90	125	170	70	tr.	10
Ba	335	155	70	70	490	62	325	72

	41	42	43	44	45	46	47	48
SiO_2	56.80	62.34	37.29	48.57	32.89	49.20	38.24	48.94
TiO_2	0.95	0.54	0.51	2.51	1.89	0.78	0.60	0.81
Al_2O_3	15.47	16.94	9.34	11.87	11.06	15.99	12.86	17.19
Fe_2O_3	2.52	1.91	0.34	12.51	5.31	1.70	0.72	2.81
FeO	5.05	3.74	3.96	1.83	3.82	3.89	4.75	4.05
MnO	0.05	0.10	0.09	0.25	0.46	0.15	0.15	0.11
MgO	5.79	3.29	3.20	4.03	3.04	3.36	5.79	3.36
CaO	5.82	5.43	23.26	4.20	21.14	6.15	12.90	4.00
Na_2O	3.06	3.54	2.09	2.91	2.53	5.62	3.43	7.35
K_2O	2.41	1.44	1.17	1.90	0.96	3.50	3.64	2.28
H_2O+	1.53	0.83	0.90	3.80	1.12	1.82	1.86	3.83
H_2O-	0.07	0.05	0.12	4.95	1.83	0.61	0.31	0.44
P_2O_5	0.05	0.01	0.18	0.59	0.55	0.18	0.17	0.16
CO_2	0.00	0.00	17.86	0.09	13.38	7.06	14.46	4.62
	99.57b	100.16b	100.31a	100.01a	99.98a	100.01a	99.88a	99.95a
Cr	300*	435*	6*	17*	52*	145*	93*	85*
V	155	156	103	235	244	270	136	275
Ni	91	49	11	17	19	39	28	43
Co	23	20	12	44	25	56	19	39
Sc	18	41	17	45	16	tr.	26	tr.
Zr	325	173	35	270	455	87	47	124
Sr	305	365	190	335	695	280	240	200
Ba	640	490	305	625	365	475	500	335

	49	50	51	52	53	54	55	56
SiO_2	40.72	41.50	42.83	41.82	50.94	38.23	48.93	50.47
TiO_2	2.38	3.51	1.59	1.34	2.67	1.49	0.99	1.10
Al_2O_3	13.88	12.64	13.68	20.54	13.53	13.12	17.63	14.14
Fe_2O_3	3.57	6.92	8.56	5.67	1.97	4.55	0.98	2.83
FeO	10.50	5.22	2.65	2.56	9.45	3.68	8.08	7.29
MnO	0.26	0.11	0.19	0.18	0.17	0.10	0.16	0.17
MgO	9.08	7.61	8.39	5.05	6.81	5.21	9.18	7.38
CaO	5.56	5.70	3.99	8.52	10.95	14.37	10.67	8.38
Na_2O	1.36	1.98	2.44	0.81	2.37	2.08	2.81	4.24
K_2O	1.74	1.76	1.24	1.15	0.43	0.75	0.23	0.38
H_2O+	8.06	5.23	5.61	6.25	0.24	3.38	0.07	2.79
H_2O-	2.49	6.11	8.69	5.41	0.08	4.44	0.02	0.44
P_2O_5	0.21	0.46	0.09	0.14	0.28	0.19	0.10	0.15
CO_2	0.12	1.50	0.28	0.10	0.38	7.77	0.01	0.09
	99.93a	100.25a	100.23a	99.54a	100.27a	99.36a	99.86g	99.85h
Cr	210*	53*	182*	260*	360*	270*	400	250
V	125	420	300	235	335	190	300	260
Ni	24	48	51	69	95	124	200	110
Co	33	53	38	52	66	42	50	42
Sc	59	68	tr.	32	tr.	34	50	40
Zr	151	140	30	90	115	165	90	140
Sr	230	390	140	1250	465	785	300	220
Ba	635	420	230	245	135	430	100	150

	57	58	59	60	61	62	63	64
SiO_2	50.73	45.67	51.40	49.38	61.1	43.8	45.6	49.22
TiO_2	2.62	3.23	1.52	1.44	0.21	1.5	1.6	2.35
Al_2O_3	13.74	14.96	16.33	15.39	7.8	11.4	14.0	14.64
Fe_2O_3	1.83	1.62	7.06	4.87	3.3	4.1	1.2	
FeO	9.45	12.71	1.98	6.24	9.6	7.3	9.4	12.37, Fe as Fe_2O_3
MnO	0.17	0.23	0.15	0.18	0.21	0.16	0.16	0.20
MgO	7.23	7.26	5.34	6.49	4.8	14.2	10.15	7.64
CaO	11.22	9.49	8.28	10.55	2.0	7.5	6.5	
Na_2O	2.20	2.77	3.82	2.71	4.6	1.6	2.2	2.45
K_2O	0.46	0.89	2.02	0.49	0.10	0.07	0.21	1.00
H_2O+	0.02	0.02	0.57	1.48	1.1	6.1	6.0	
H_2O-	0.14	0.18	0.65	0.59	0.10	1.7	0.74	
P_2O_5	0.22	0.99	0.68	0.22	0.22	0.15	0.15	
CO_2	0.01	0.01	0.01	0.02	0.53	0.05	1.4	
FeS_2					3.7	0.01	0.02	
	100.04g	100.03j	99.81k	100.05m	99.37n	99.64n	99.33n	
Cr	400	250	400	270	30	300	150	170
V	300	300	200	360	300	70	70	250
Ni	100	94	100	81	70	700	300	130
Co	50	39	50	41	15	70	15	48
Sc	40	40	70	58	3	7	7	30
Zr	200	370	200	100	70	30	30	140
Sr	700	300	900	190	15	30	70	465
Ba	130	580	800	260	3	15	70	330

	65	66	67	68	69	70	71	72
SiO_2	58.42	5.14	51.90	49.65	49.32	44.03		
TiO_2	0.77	0.07	1.30	0.45	1.15	2.62	1.30	2.23
Al_2O_3	15.12	0.79	16.02	8.37	8.03	12.85		
Fe_2O_3	Fe as Fe_2O_3 6.75	0.54	3.53	4.10	0.68	5.68		
FeO			7.34	9.29	12.82	11.52		
MnO	0.11	0.14	0.12	0.21	0.40	0.20	0.26	0.27
MgO	2.49	7.80	5.72	14.12	16.25	8.54	8.28	6.28
CaO			6.16	11.78	10.13	9.66	9.70	8.38
Na_2O	1.31	0.05	3.44	1.29	1.03	2.21		
K_2O	3.21	0.33	2.37	0.55	2.04	0.78	1.86	1.88
H_2O+			0.64	0.15	0.17	1.46		
H_2O-			0.02	0.02	0.00	0.04		
P_2O_5			0,80	0.05	0.02	0.22		
CO_2			0.00	0.00	0.00			
			99.36b	100.03b	100.49b	99.81p	q	q
Cr	90	11	100#	2400#	1400#	165#	215#	73#
V	130	20	250	265	225	1075	455	775
Ni	68	20	44	128	520	64	55	42
Co	19	0.1	24	55	88	76	49	60
Sc	13	1	36	72	31	42	38	42
Zr	160	19	300	28	105	200	100	150
Sr	300	610	620	40	25	100	116	88
Ba	580	10	560	70	112	94	125	120

	73	74	75	76	77	78	79	80
SiO_2	49.72	50.55	52.66	53.73	44.04	45.06	46.36	48.1
TiO_2	2.13	1.28	2.45	1.70	2.91	2.15	1.51	1.3
Al_2O_3	13.53	17.08	12.09	14.47	12.46	17.84	18.39	13.4
Fe_2O_3	3.99	0.36	6.74	1.14	2.49	0.67	0.58	1.1
FeO	10.68	11.80	13.25	13.68	16.88	16.21	14.33	13.1
MnO	0.24	0.16	0.34	0.36	0.32	0.49	0.35	0.3
MgO	6.29	5.80	1.91	5.24	6.29	5.33	5.75	9.7
CaO	9.54	10.47	6.46	8.66	10.04	9.85	10.62	10.8
Na_2O	1.58	1.67	3.42	0.49	2.56	1.63	1.59	1.6
K_2O	0.92	0.12	0.22	0.16	0.64	0.16	0.08	tr.
H_2O+	1.40	0.56	0.39	0.42	1.18	0.86	0.54	0.5
H_2O-	0.03	0.00	0.03	0.00	0.02	0.03	0.03	
P_2O_5	0.16	0.09	0.36	0.04	0.07	0.08	0.10	0.1
CO_2								
	100.21p	99.94f	100.32f	100.09f	99.90f	100.36f	100.23f	100.0f

Cr	69#	68*	12*	32*	10*	49*	60*	58*
V	480	265	49	430	550	600	305	610
Ni	44	47	10	30	67	114	60	73
Co	53	48	31	56	70	55	51	83
Sc	42	41	40	44	53	30	55	80
Zr	87	80	1190	185	185	100	200	150
Sr	78	125	160	140	65	105	90	74
Ba	54	175	260	17	170	21	10	160

	81	82	83	84	85	86	87	88
SiO_2	45.6	49.36	51.34	48.96	48.13	54.68	51.89	50.45
TiO_2	3.0	1.80	1.99	2.27	1.87	2.06	1.49	2.48
Al_2O_3	13.1	17.47	14.68	15.27	17.34	14.43	13.75	14.03
Fe_2O_3	0.4	3.09	5.37	5.11	2.51	4.91	2.82	5.54
FeO	19.0	10.55	9.03	9.18	8.18	8.10	6.20	9.22
MnO	0.3	0.12	0.26	0.22	0.22	0.24	0.13	0.24
MgO	5.8	3.89	4.40	5.13	6.58	3.50	6.25	4.89
CaO	12.2	11.36	6.91	7.17	8.09	4.02	9.98	6.56
Na_2O	0.6	1.04	3.85	4.30	3.95	5.55	4.22	4.32
K_2O	tr.	0.41	0.43	0.70	0.76	0.44	0.61	0.53
H_2O+	0.0	0.55	H_2O 1.94	2.00	2.00	1.71	1.79	1.59
H_2O-		0.00						
P_2O_5	0.1	0.08	0.27	0.32	0.24	0.45	0.21	0.29
CO_2							present	
	100.1f	99.72f	100.47d	100.63d	99.87d	100.09d	99.34d	100.14d
Cr	55*	54*	22*	44*	185*	n.d.*	425*	23*
V	270	365	445	455	280	165	220	370
Ni	75	69	17	36	67	8	132	20
Co	43	58	32	43	40	26	30	32
Sc	70	80	57	51	40	35	42	30
Zr	100	195	168	380	310	505	245	235
Sr	70	165	29	93	225	55	139	82
Ba	30	72	66	58	145	110	130	50

	89	90	91	92	93	94	95	96
SiO_2	44.66	44.78	46.46	46.52	46.13	49.38	49.01	44.97
TiO_2	2.94	2.03	1.33	1.10	0.99	0.64	0.93	2.05
Al_2O_3	12.91	14.50	16.73	14.00	15.18	16.53	14.84	13.73
Fe_2O_3	3.21	5.90	2.56	2.42	4.7	2.4	2.3	6.7
FeO	13.93	9.17	8.06	8.00	10.02	7.65	10.12	10.65
MnO	0.36	0.34	0.20	0.17	0.30	0.20	0.22	0.22
MgO	10.02	8.94	8.37	12.88	6.4	4.3	5.1	1.9
CaO	6.09	7.21	9.60	9.78	13.5	16.5	12.4	16.9
Na_2O	1.95	3.80	3.36	2.45	1.11	0.78	1.61	0.77
K_2O	0.27	0.40	0.55	0.46	0.31	0.17	0.26	0.32
H_2O	2.98	2.09	1.86	2.56				
P_2O_5	0.30	0.29	0.16	0.08	0.13	0.08	0.12	0.88
CO_2			0.40					
	99.62d	99.45d	99.64d	100.42d	e	e	e	e

Cr	12#	130#	300#	1080#	315*	360*	475*	tr.*
V	300	300	300	300	380	350	430	185
Ni	24	50	210	465	93	128	175	8
Co	51	42	48	53	70	42	52	34
Sc	60	36	28	30	65	58	47	46
Zr	315	195	150	90	90	49	99	175
Sr	55	140	315	140	238	235	260	390
Ba	90	38	140	60	84	68	118	165

	97	98	99	100	101	102	103	104
SiO_2	49.36	49.55	49.02	48.34	53.32	53.62	50.05	51.58
TiO_2	0.65	2.00	1.75	1.44	1.76	0.80	1.04	0.72
Al_2C_3	16.89	12.14	14.08	13.85	11.86	15.43	14.48	15.43
Fe_2O_3	1.5	3.9	4.8	3.1	3.4	7.3	1.5	3.8
FeO	7.25	12.37	10.97	10.81	12.31	2.14	10.89	8.4
MnO	0.15	0.28	0.28	0.22	0.34	0.22	0.21	0.17
MgO	3.5	6.5	6.4	5.6	5.1	5.2	7.2	3.9
CaO	16.5	9.2	9.6	10.7	9.3	8.3	9.8	14.6
Na_2O	1.30	2.48	3.03	2.39	2.36	2.78	2.36	1.14
K_2O	0.15	0.19	0.19	0.25	0.34	2.48	0.82	0.21
P_2O_5	0.05	0.28	0.25	0.17	0.35	0.31	0.13	0.09
	e	e	e	e	e	e	e	e
Cr	380*	330*	260*	350*	140*	590*	200*	215*
V	285	570	585	395	295	290	320	255
Ni	147	115	92	129	47	140	68	107
Co	56	58	53	56	45	37	44	56
Sc	73	66	80	65	23	37	63	47
Zr	40	350	185	170	220	200	93	74
Sr	205	150	165	140	110	365	163	168
Ba	66	75	81	58	85	875	122	49

	105	106
SiO_2	48.88	55.82
TiO_2	0.86	2.09
Al_2O_3	15.49	10.01
Fe_2O_3	2.4	4.5
FeO	8.39	11.82
MnO	0.20	0.38
MgO	5.5	4.4
CaO	15.6	9.4
Na_2O	2.13	0.92
K_2O	0.18	0.17
P_2O_5	0.10	0.31

	107	108	109	110	111	112	113
Cr	430*	400*	150*	380*	91*	125*	150*
V	185	190	470	260	240	360	225
Ni	124	36	62	94	45	24	10
Co	44	52	85	43	28	33	32
Sc	29	42	29	34	20	57	33
Zr	235	41	255	50	345	295	94
Sr	170	210	175	155	760	170	240
Ba	305	205	130	105	50	34	305

	e	e
Cr	145*	26*
V	255	375
Ni	84	39
Co	52	48
Sc	50	36
Zr	63	310
Sr	180	100
Ba	23	10

Major element Analysts

a. J. Muysson, McMaster University

b. H.B. Wiik

c. W.H. Herdsman

d. B.E. Leake

e. G.K. Billings (MnO spectrographic by P.C. van de Kamp)

f. R.A. Binns (80,81 are calculated from mineral analyses)

g. D. Powers and P.R. Barnett

h. J. Goldsmith and N. Conklin

j. L. Trumbull and P.R. Barnett

k. L.C. Peck and R.S. Harner

m. R. Kittrell and P.R. Barnett

n. P.D. Elmore, I.H. Barlow, S.D. Botts, and G. Chloe

p. C.G. Engel

q. A.A. Chodos (X-Ray fluorescence)

APPENDIX 2

SAMPLE LOCALITIES AND DESCRIPTIONS

ORTHO-AMPHIBOLITES

Analysis Number	Sample Number	Locality and Description
111	K.L. - 1	Teck Township, Ontario, 4500 feet S.E. of intersection of Highways 66 and 112 west of Kirkland Lake. Rocks are basaltic pillow lavas transformed to amphibolite in the aureole of a syenite intrusive. They are made up of hornblende, plagioclase, biotite, and chlorite. Reference: Thomson (1948)
2	K.L. - 2	
1	Hamburg - 1	Sussex County, New Jersey, about 6 miles N.E. of Hamburg. Amphibolite with relict pillow structures composed of plagioclase, hornblende, biotite, scapolite, pyroxene, calcite, and sphene. Reference: Hague et al. (1956)
108	- 2	
109	- 3	
3	Adirondack - 1	North side of Newport Pond, Elizabethtown Quadrangle, Adirondack Mountains, New York. No. 1 represents a fine-grained border phase and No. 2 a coarse-grained phase. Mineralogy includes pyroxene, hornblende, garnet, plagioclase, sphene, and magnetite.
110	- 2	
4	RH 153-55	Beartooth Mountains, Wyoming. Amphibolite composed of quartz, plagioclase, hornblende, magnetite, apatite, biotite, sericite, and epidote. Reference: Harris (1959)
5	RDB - 42B	Beartooth Mountains, Montana. Samples collected by R.D. Bentley for report in preparation
6	47	
7	56	
8	135	
9	218	
10	265	
11	238	
17	44	Broken Hill, Australia. Metagabbro composed of pyroxene, hornblende, plagioclase, magnetite, garnet, and apatite. Reference: Binns (1962)

PARA-AMPHIBOLITES

Analysis Number	Sample Number	Locality and Description
37 40 38 39	DE 41-53 DE 227-54 DE 125-53 DE 131-54	Beartooth Mountains, Montana, Quad Creek Area. Para-amphibolites composed of plagioclase, pyroxene, quartz, hornblende, biotite, magnetite, and apatite. Reference: Eckelmann and Poldervaart (1957)
42	92-55	Beartooth Mountains, Wyoming. Granitized para-amphibolite composed of hornblende, plagioclase, biotite, quartz, microcline, apatite, and magnetite. Reference: Harris (1959)
30 31 32 33 34 35 36	PA - 16 - 17 - 19 - 21 - 22 - 23 PAQ- 1	Beartooth Mountains, Montana. Samples collected by R.D. Bentley for report in preparation
28	Detlor 12	Dungannon Township, Ontario, Detlor Road, ½ mile E. of Detlor Station. Feather amphibolite from 8-inch band in marble. Contains hornblende, plagioclase, and magnetite. Reference: Hewitt and James (1956)
29	Kaladar - 1	Roadcut along Highway 41, 2 miles N. of Kaladar, Ontario. Mineralogy includes plagioclase, quartz, hornblende, epidote, biotite, microcline, and diopside. Rock is a conglomerate matrix. Reference: Walton et al. (1964)
26 27	Limerick - 7 - 9	Limerick Township, Ontario, from roadcuts along Highway 62. Rocks are graywackes which have been metamorphosed under upper greenschist and epidote-amphibolite conditions.
25 113 114	Hibernia - 1 - 2 - 3	Hibernia, New Jersey, Hibernia Mine Area. Amphibolites intercalated with quartzofeldspathic gneisses. Composed of plagioclase, pyroxene, hornblende, and biotite. Reference: Sims (1958)

Analysis Number	Sample Number	Locality and Description
41 112	Z - 5 Z - 8	Beartooth Mountains, Wyoming. Rocks contain quartz, microcline, plagioclase, hornblende, biotite, opaques, apatite, sphene, zircon, epidote, and allanite. Reference: Harris (1959)
Table 7, R	Madoc - 2	Madoc Township, Ontario, Stoklosar Quarry. An amphibolite formed by metasomatism of marble by granite. Contains amphibole and calcite.

AMPHIBOLITES OF UNCERTAIN ORIGIN

83 84 85 86 87 88 89 90 91 92	BL - 165 - 360 RB - 522 BL - 2506 - 2515 - 2522 - 2518 - 194 - 7634 - 2516	Connemara, Ireland. Composed of hornblende, plagioclase, chlorite, quartz, pyroxene, biotite, epidote, sphene, apatite, and opaque minerals Reference: Evans and Leake (1960)
74 75 76 77 78 79 80 81 82	1 3 9 12 13 14 28 29 37	Broken Hill, Australia. Mineralogy includes quartz, hornblende, plagioclase, pyroxene, garnet, ilmenite, and apatite. Reference: Binns (1962)
93 94 95 96 97 98 99 100	L 4 L 5 L 8 L10 L12 L13 L14 L15	Llano County, Texas. Packsaddle Schist. Composed of quartz, hornblende, plagioclase, pyroxene, potash feldspar, biotite, sphene, apatite, zircon, garnet, and opaque minerals. Reference: Billings (1962)

Analysis Number	Sample Number	Locality and Description
101	L 16	
102	LW 2	
103	HC 2	
104	HC13	
105	HC15	
106	HC16	
	SEDIMENTS AND TUFFS	
46	Lockatong - 1	New Jersey, Lockatong Argillite, Triassic, composed of illite, feldspar, analcime, dolomite, and minor calcite and quartz. Reference: Van Houten (1960, 1962)
47	- 2	
48	- 3	
44	SR - 64 - 24	Government Point, one mile N. of Depee Bay, Cape Foulweather Quadrangle, Oregon. Basaltic sandstone and pebble conglomerate (graywacke) associated with late (?) Miocene flows.
45	Yachats - A	Intersection of west section line 23 with coast, 1.5 miles north of Yachats. T.14S., R.12W., Waldport Quadrangle, Washington. Oligocene.
43	Limerick - 4	Limerick Township, Ontario, Highway 62 near southern boundary of township. Graywacke with knots of hornblende and chlorite.
49	JCC - 1	Sec. 27, T.13S., R.4W., near Halsey, Oregon. Gulf Oil Co. well, T.J. Porter No. 1. core sample of tuff breccia from 8100 ft. depth. Eocene.
50	JCC - 2	Sec. 27, T.14S., R.8W., East of Tillamook, Oregon. Core sample from drill hole. Contains palagonite, nontronite, plagioclase, clinopyroxene, glass, analcime, and heulandite. Eocene.
51	JCC - 3	Sec. 28, T.10S., R.4W., Coffin Butte, Oregon. Tuff from a quarry. Eocene.
52	JCC - 4	Sec. 2, T.13S., R.7W., Alsea Quadrangle, Oregon. Zeolitic pillow lava from road cut along State Highway 34. Eocene.

Analysis Number	Sample Number	Locality and Description
54	La Honda	Langley Hill - Mindego Hill area, La Honda, California. Tuff with intermixed carbonates. Miocene. Reference: Haehl and Arnold
53	Hawaii	Kaimu Beach, Puna District, S.E. coast of Hawaii. Basaltic glass sand containing about 1% calcareous shell fragments, possibly from 1750 or 1780 eruption.

ADDENDA

ORTHO-AMPHIBOLITES

12	69-30-2	Chandos Township, Ontario
13	69-28-5	Ref. Kudo (1962)
14	69-30-6	
15	69-34-7	
16	69-35-7	
18	69-28-2	

PARA-AMPHIBOLITES

19	68-78-1	Chandos Township, Ontario
20	70-146-6	Ref. Kudo (1962)
21	70-139-1	
22	68-74-16	
23	69-27-2	
24	69-32-1	

APPENDIX 3

Sums of squares and mean squares

for precision of spectrographic analyses

		d.f.	s.s.	m.s.
Element Cr	Between Groups	65	95.70931	1.47245
	Within Groups	195	2.50259	0.01283
	Total	260	98.21190	
V		50	5.02166	0.10043
		150	1.30703	0.00871
		200	6.32869	
Ni		65	26.01425	0.40022
		195	0.44869	0.00230
		260	26.46294	
Co		65	4.60999	0.07215
		195	0.49182	0.00252
		260	5.18181	
Sc		65	25.70582	0.39547
		195	1.86779	0.00958
		260	27.57361	
Zr		50	15.35915	0.30718
		150	2.49776	0.01665
		200	17.85691	
Sr		65	15.84743	0.24381
		195	2.42590	0.01244
		260	18.27333	
Ba		65	36.64499	0.56377
		195	3.57125	0.01831
		260	40.21624	

APPENDIX 4

SSP Matrices

pA n = 16

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
259476.00	9665.50	56747.50	3186.50	14266.00	-41147.50	-2616.00	-66474.50	Cr
	164858.44	17799.94	17268.81	11500.88	54606.69	-39664.63	-158562.56	V
		21565.44	3510.31	4929.88	-16665.81	-18487.63	-54093.06	Ni
			2814.94	2047.63	2234.56	-9059.88	-19030.19	Co
				3381.75	-3050.62	-6959.25	-19718.13	Sc
					201147.94	155105.88	27659.69	Zr
						321577.75	123732.38	Sr
							555482.44	Ba

APPENDIX 5

oA n = 16

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
691781.75	10690.63	65152.75	-12385.63	17734.50	-296061.25	-70393.38	-39996.50	Cr
	261614.94	24942.63	19261.06	16289.75	12961.63	-85892.56	-189611.75	V
		27779.75	-2278.63	10073.50	-14012.25	-5395.38	3993.50	Ni
			6048.94	-3050.75	2824.38	-5728.44	-14301.25	Co
				14275.00	22117.50	-4456.25	-20751.00	Sc
					361463.75	74940.63	-10596.50	Zr
						178361.94	127555.25	Sr
							573145.00	Ba

APPENDIX 6

SSP Matrices

16 pA and 16 oA

Between Groups SSP Matrix n = 32

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
1494720.50	682955.00	386863.75	138320.00	113249.50	8212.75	-155177.75	-497519.75	Cr
	312050.00	176762.50	63200.00	517450.00	3752.50	-70902.50	-227322.50	V
		100128.13	35800.25	29311.25	2125.63	-40163.13	-128768.13	Ni
			12800.00	10480.00	760.00	-14360.00	-46040.00	Co
				8580.50	622.25	-11757.25	-37695.25	Sc
					45.13	-852.63	-2733.63	Zr
						16110.13	51651.13	Sr
							165600.13	Ba

APPENDIX 7

Within Groups SSP Matrix n = 32

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
951257.75	20356.13	121900.25	-9199.13	32000.50	-33720.88	-73009.38	-106471.00	Cr
	426473.38	42742.56	36529.88	27790.63	67568.31	-125557.19	-348174.31	V
		49345.19	1231.69	15003.38	-30678.06	-23883.00	-50099.56	Ni
			8863.88	-1003.13	5063.94	-14788.31	-33331.44	Co
				17656.75	19066.88	-11415.50	-40469.13	Sc
					562611.69	230046.50	17063.19	Zr
						499939.69	251287.63	Sr
							1128627.44	Ba

APPENDIX 8

Covariance Matrices (Dispersion Matrices)

Pooled within groups covariance matrix n = 32

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
7549.66	161.56	967.46	-730.09	253.97	-2676.26	-579.44	-845.01	Cr
	338.47	339.23	289.92	220.56	536.26	-996.49	-2763.29	V
		391.63	9.78	119.07	-243.48	-189.55	-397.62	Ni
			70.35	-7.96	40.19	-117.37	-264.54	Co
				140.13	151.32	-90.60	-321.18	Sc
					4465.17	1825.77	135.42	Zr
						3967.78	1994.35	Sr
							8957.36	Ba

APPENDIX 9

Inverse pooled within groups covariance matrix n = 32

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
0.000164	0.000411	0.000470	0.013635	0.026077	0.005067	0.000661	0.000258	Cr
	-0.000048	-0.000236	-0.000981	0.006540	-0.000790	-0.000271	0.000007	V
		-0.000007	0.000493	-0.000315	-0.003317	-0.002258	-0.000493	Ni
			0.000226	0.000375	0.000154	-0.000620	0.000122	Co
				0.000206	-0.000048	-0.000077	-0.000242	Sc
					-0.000039	0.000063	0.000160	Zr
						0.000091	-0.000066	Sr
							0.000012	Ba

BEARTOOTH AMPHIBOLITES

APPENDIX 10

8 oA, SSP matrix

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
624096.00	83956.00	53228.00	1666.00	37548.00	-12168.00	-87134.00	-36826.00	Cr
	25373.50	12865.00	2297.25	10503.00	-2729.00	-37930.25	21468.50	V
		8856.00	1425.50	5998.00	1865.00	-22619.50	17676.00	Ni
			549.88	1311.50	-823.00	-5988.38	3308.75	Co
				5046.00	-3664.00	-18329.50	129.00	Sc
					26144.00	1672.00	67309.00	Zr
						78982.88	-54714.75	Sr
							300741.50	Ba

APPENDIX 11

8 pA, SSP matrix

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
531137.50	50246.25	8901.25	-23660.00	27693.75	-67975.00	-53727.50	-83258.75	Cr
	19750.88	9568.88	2531.50	5871.13	-19300.50	-21624.25	-22216.63	V
		7352.88	4051.50	1643.13	-6395.50	-8300.25	-6920.63	Ni
			17456.00	-1790.50	-5887.00	-2039.00	2133.50	Co
				3060.88	-4912.50	-5157.75	-5563.38	Sc
					37194.00	33135.00	44384.50	Zr
						36859.50	42006.75	Sr
							60503.88	Ba

APPENDIX 12

Covariance matrix (Pooled within Groups)

Beartooth Mountains 8oA + 8pA

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
8256.68	9585.88	4437.80	-1571.00	4660.13	-5724.50	-10061.54	-8577.48	Cr
	3223.19	1602.42	344.91	1169.58	-1573.54	-4253.89	-53.44	V
		1157.78	391.21	545.79	-323.61	-2208.55	768.24	Ni
			1286.13	-34.21	-479.29	-573.38	388.73	Co
				604.78	-612.61	-1677.66	-388.17	Sc
					4524.14	2486.21	7978.11	Zr
						8274.46	-907.71	Sr
							25803.24	Ba

APPENDIX 13

Inverse of pooled within groups Covariance Matrix

Cr	V	Ni	Co	Sc	Zr	Sr	Ba	
0.00018	0.00060	0.00154	0.00819	0.00138	0.00993	0.00302	0.00003	Cr
	0.00016	-0.00049	-0.00079	0.00030	-0.00130	-0.00248	-0.00003	V
		-0.00046	0.00086	0.00070	0.00103	0.00034	-0.00006	Ni
			0.00030	-0.00019	-0.00155	-0.00227	0.00004	Co
				-0.00019	0.00060	0.00101	-0.00017	Sc
					0.00037	0.00008	0.00002	Zr
						-0.00028	-0.00004	Sr
							-0.000002	Ba

APPENDIX 14

Major Elements

80 Amphibolites

40 ortho-amphibolites SSP matrix

TiO_2	Fe_2O_3	FeO	MgO	CaO	P_2O_5	
36.364	15.235	79.837	-47.811	-24.687	5.391	TiO_2
	61.791	-4.895	-17.276	-52.754	6.333	Fe_2O_3
		333.396	-62.953	-11.314	4.097	FeO
			274.166	9.302	-12.821	MgO
				2.313	-13.301	CaO
					3.540	P_2O_5

APPENDIX 15

40 para-amphibolites SSP Matrix

TiO_2	Fe_2O_3	FeO	MgO	CaO	P_2O_5	
11.369	2.579	19.596	-16.063	-1.070	1.386	TiO_2
	63.313	32.218	1.357	-18.370	-0.979	Fe_2O_3
		202.309	69.980	58.323	0.636	FeO
			385.047	83.638	-1.780	MgO
				356.326	-0.446	CaO
					0.845	P_2O_5

APPENDIX 16

Covariance Matrix (Pooled within groups)

TiO_2	Fe_2O_3	FeO	MgO	CaO	P_2O_5	
0.6121	0.2284	1.2748	-0.8189	-0.3302	0.0869	TiO_2
	1.6039	0.2862	-0.2041	-0.9119	0.0686	Fe_2O_3
		6.8757	0.0901	0.6027	0.0607	FeO
			8.4514	1.1922	-0.2644	MgO
				7.5334	-0.1762	CaO
					0.0562	P_2O_5

APPENDIX 17

Inverse of pooled within groups covariance matrix

TiO_2	Fe_2O_3	FeO	MgO	CaO	P_2O_5	
26.6875	0.1549	0.1584	0.2858	0.7082	4.2858	TiO_2
	0.2964	-0.0023	-0.0567	0.0039	-0.2215	Fe_2O_3
		0.3959	-0.0348	-0.0283	-0.7618	FeO
			0.4812	0.0692	0.2830	MgO
				-0.4491	0.0852	CaO
					-3.9334	P_2O_5