THE GEOLOGY, PETROLOGY AND GEOCHEMISTRY
OF THE
TEIZI METANORTHOSITE.

C.M. Gray, B.Sc.

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Department of Geology,
University of Adelaide.

Supervisor: R W Nesbitt

ABSTRACT

A study was made of the detailed geology, petrology and geochemistry of the Teizi Metanorthosite of Central Australia. The body is a metamorphosed stratiform anorthosite with marked lithologic layering.

The geology is presented as a geological map, discussion of structure and lithology and a sequence of events.

Major and trace element analyses of a suite of plagioclases show composition variation and define an antiperthite composition field.

Whole rock analyses provide geochemical information, allow interpretation of mineral assemblages and comparison with experimental investigations of basic rock metamorphism.

Classification and genesis of the Teizi Metanorthosite and anorthosites in general is discussed.

INTRODUCTION

The Teizi Metanorthosite (area: 11.4 square miles), is located in the Tomkinson Ranges of north-western South Australia. The geology of the area is dominated by a granulite facies metamorphic terrain and the intrusive, basic Giles Complex. The vicinity of the metanorthosite shows a complex history of granulite facies metamorphism and dyke and plug intrusion.

HISTORY

Little previous geological work has been done. The body was originally mapped by Southwestern Mining Company geologists in the period 1954-57, being considered by them to be part of the Giles Complex. Later mapping based on this by the South Australian Department of Mines resulted in the Mann 4-mile and Davies 1-mile sheets on which the metanorthosite is shown in varying detail with generally massive character. Dr. R.L. Oliver also briefly visited the locality in 1963.

The present investigation involved field mapping to elucidate lithologic relations and structure, and collection of geochemical samples during three weeks in May, 1967.

GEOLOGY

GEOLOGIC DIVISIONS

The rocks outcropping in the area can be considered as - granulite country rock, metanorthosite massif and various dykes and plugs.

The metanorthosite is a macro-layered body, with variation from metanorthosite (100% plagioclase) to orthopyroxene-plagioclase gneiss and (rarely) orthopyroxene rock. The lithologic units, which are reasonably easy to differentiate in the field are:

Field Name	Lithology
Core gabbroic metanorthosite	Gabbroic metanorthosite
Core gneissic unit	Heterogeneous
Core massive metanorthosite	Metanorthosite
Core blue metanorthosite	Metanorthosite
Inner layered unit	Pyroxene-plagioclase gneiss
Outer blue metanorthosite	Metanorthosite
Outer layered unit	Pyroxene-plagioclase gneiss
Outer massive metanorthosite	Metanorthosite
Basic granulite	Various pyroxene granulites

The total thickness is approximately 4,500 feet.

These units define an antiformal structure conformable with the country rock layering. The boundary between the metanorthosite and the country rock is difficult to define and will be discussed later.

There are two major trends of dykes crosscutting the area. Large vertical foliated dykes of NW-SE trend cut the eastern end of the metanorthosite, while smaller, but more significant dykes of slightly different trend occur in great profusion in the body itself.

Finally, a small picrite plug of the Giles Complex intrudes the metanorthosite, crosscutting the second class of dykes.

STRUCTURE

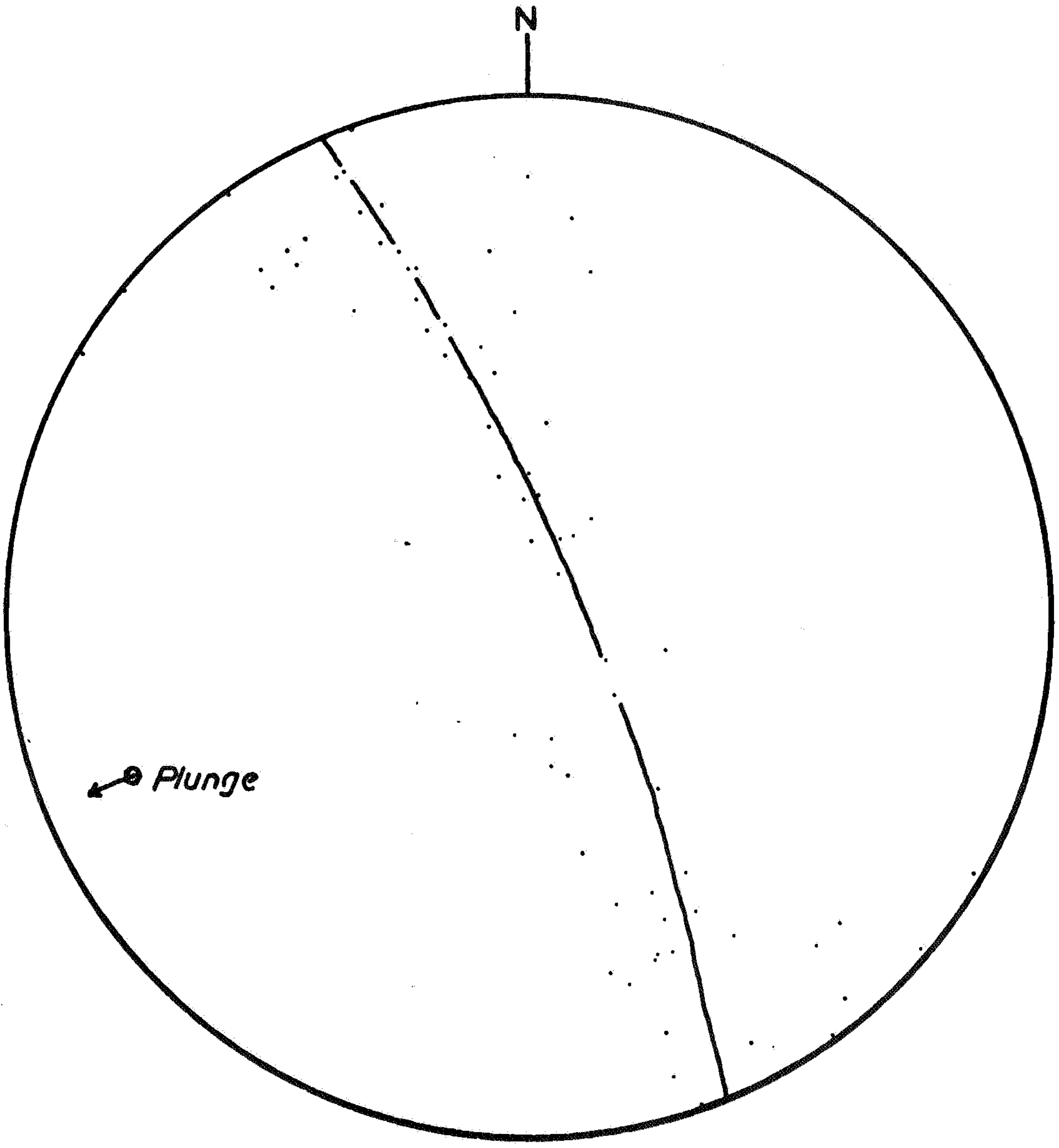
Fold Structure

The major antiformal fold structure needs little description. A stereographic plot of the orientation of poles to layering and foliation (see Fig. 1) defined a great circle whose pole gives a plunge of 12° in the direction 247°. No difference in resulting fold orientation is obtained by plotting either foliation or layering separately, and when seen together in the field they are almost always concordant. The northern limb is roughly vertical with some variation in dip (-80 to +80°), the southern dipping progressively from 20° to 60° south. Mesoscopic structures are rare, the only one found in place being in a mylonite displacing the inner layered unit with orientation and style a mirror of the large scale structure.

Foliation

The rocks being dominantly feldspathic, the foliation is defined by pyroxene in the form of elongate granular lenses. Large crystals of orthopyroxene in the core rocks, particularly

FIGURE I : STEREOGRAPHIC PLOT OF POLES TO LAYERING AND FOLIATION



near the contact with the inner layered unit, show varying degrees of deformation and rotation into the plane of the foliation. The origin of this structure will be discussed later.

Layering

Layering in two scales occurs in the body. There is the major layering briefly described above and small-scale lithologic layering which is restricted to the "layered units" with rare occurrences in the core rocks. Both types will be described in more detail.

Faulting

Three main directions of faulting are found, each with its development of basic dykes (see Fig. 2).

Type (1) are constant in orientation, show small displacements and are localised in the plane of the dyke. Post-dyke intrusion movements are small, with slight development of glassy "pseudotachylite". Marked displacements only occur near the nose of the antiform, where shear zones rather than faults have displacements parallel to the trend of the southern limb. These shear zones (approximately 200 feet wide) contain slickensides and sheared rock and are preferred sites of dyke intrusion. Greater displacement and intensity of faulting in this region are obviously related to greater stress in the nose of the fold.

Type (2) show a greater development of shearing and mylonitisation. A dyke lithologically similar to those along type

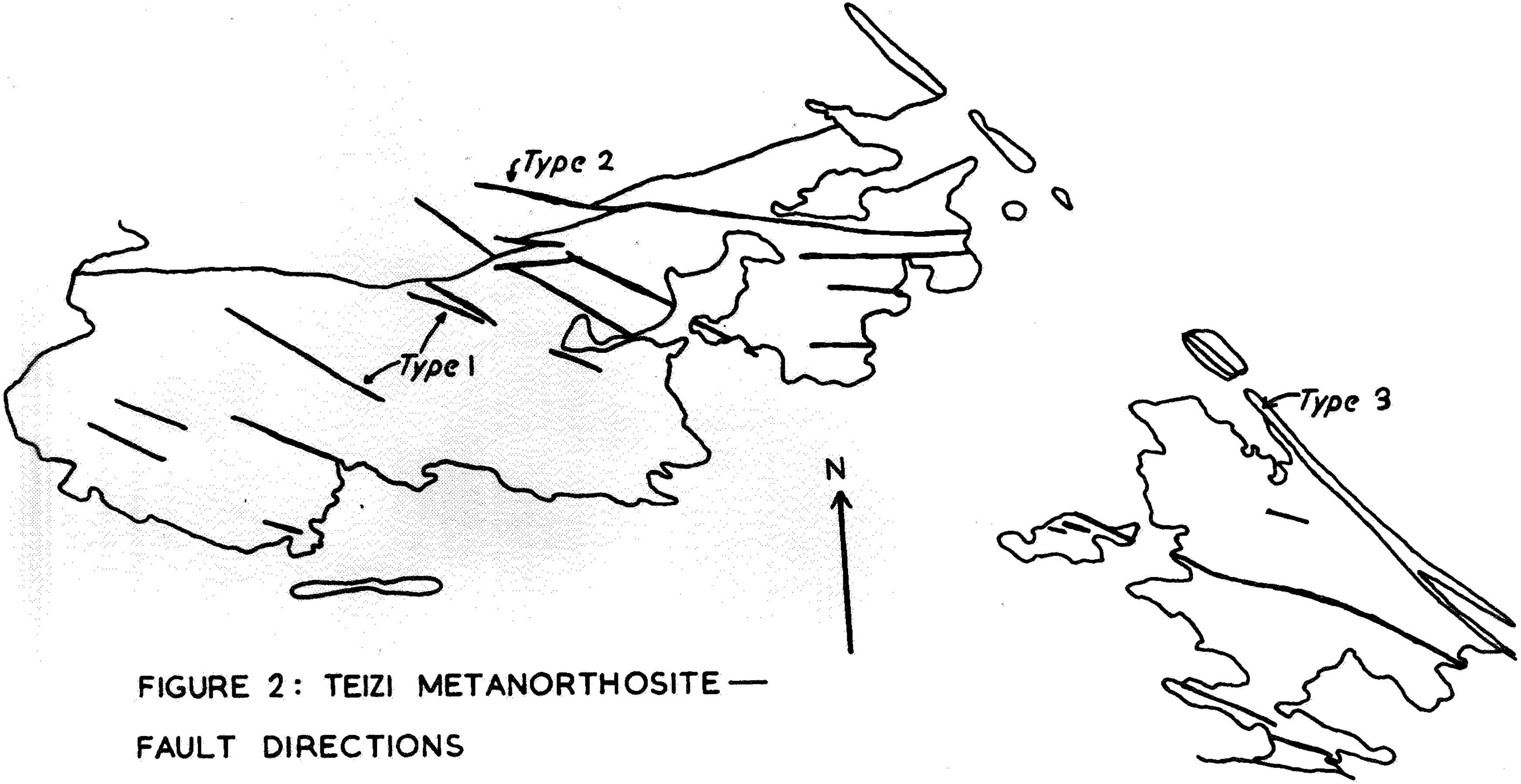


FIGURE 2: TEIZI METANORTHOSITE — FAULT DIRECTIONS

Fault = ——

(1) faults is itself badly sheared, with formation of "pseudotachylite" - that is, this fault was definitely active after emplacement.

Type (3) faults have not been observed, but are presumed to correspond to the major dykes of NW-SE trend.

GENERAL DESCRIPTION OF ROCK TYPES

Lithologic variation in the metanorthosite is simple, being due to change in the proportions of orthopyroxene and plagioclase and a related reduction in grain size with increasing pyroxene content. The plagioclase-rich rocks have a cataclastic texture.

Core Gabbroic Metanorthosite

This rock type, which is uniform in character, outcrops in the core of the fold as massive blocks making up woolsack tors. It consists of pleochroic orthopyroxene (15%) and antiperthitic plagioclase (85%) and is even grained in hand specimens. Plagioclase forms large interlocking grains, pyroxene is interstitial. The contact with the core gneissic unit is gradational over a short distance with some interlayering of the two rock types.

Core Gneissic Unit

The core gneissic unit is inhomogeneous, with gradation in character from even-grained, well-layered pyroxene-plagioclase gneiss to foliated gabbroic metanorthosite to pure metanorthosite

- complex interlayering is common. The northern contact varies from very sharp (layered gneiss to massive metanorthosite) to gradational (these areas shown on the map with a dotted contact)

Core Metanorthosite

There are two natural subdivisions of this major unit of the massif. The first is a coarse-grained, blue-grey metanorthosite (= Blue Metanorthosite), which occasionally has a pyroxene content over ten percent, variation being apparently random. The dominant mineral, an antiperthitic plagioclase, is arranged in a metamorphic texture with large grains having serrated, interlocking contacts. The pyroxene occurs in clumps and may form a crude foliation which swells in places to granular, augen-shaped clots.

The other type is a sheared, pure metanorthosite, which in hand specimen has a white to pale grey colour and a blotchy appearance due to shearing and fine grain size. It is strongly deformed with augen-shaped grains, distortion of plagioclase twin lamellae and granulated patches. Grain boundary alteration to calcite and a fibrous mineral is common - altered clinopyroxene is rare. The distribution of the unit is a puzzle. It forms a prominent east-west ridge in the eastern part of the body, becoming broader to the west as though it closes in the fold. Here it is difficult to map because of contained unsheared islands of blue metanorthosite, and its limits are only approximate. Intensity of deformation, presumably related to folding, is more concentrated in this rock and may in part be due to its monomineralic composition (the converse is possible). Its peculiar outcrop pattern is taken as indicating deformation intensity and not a primary feature.

The core metanorthosite becomes more mafic towards its contact with the inner layered unit and in places is markedly foliated or pegmatitic, with large pyroxene schlieren. The contact is sharp to gradational over distances of the order of a hundred feet, the actual boundary being taken as the first occurrence of prominent layering.

Inner Layered Unit

This relatively thin horizon can be followed around the antiform and is an important marker. It is a pyroxene-plagioclase ± garnet gneiss with layering (1" to 1') defined by variations in proportions of pyroxene, feldspar and sometimes garnet - in particular the assemblages plagioclase-garnet-clinopyroxene and plagioclase-orthoclase-clinopyroxene-hornblende. In the sequence are occasional coarse-grained blue metanorthosite layers (identical to the rock in the core) which are perfectly conformable. The texture of the rocks is crudely granoblastic and the plagioclase is not antiperthitic.

Outer Blue Metanorthosite

This rock type has sharp contacts with both the inner and outer layered units and is similar to the metanorthosite of the core. It is blue-grey in colour and coarse-grained, made of interlocking crystals of antiperthitic plagioclase and a small amount of orthopyroxene. Pegmatitic patches contain very large orthopyroxene crystals (up to ten inches) set in typical metanorthosite.

Outer Layered Unit

The unit is similar to the inner layered unit, but has a greater variation in lithology. More common interlayering of metanorthosite, antiperthitic plagioclase and mineralogy restriction to plagioclase and orthopyroxene are other important differences. Textures are again crudely granoblastic.

Outer Massive Metanorthosite

Although it outcrops as cream-coloured boulders, in thin section the rock is very similar to the other massive metanorthosite. Plagioclase is the only constituent and severe deformation is evidenced by a general absence of twinning, bending of what lamellae are present, undulose extinction, shear planes, areas of granulation and alignment of grains with long axes parallel - a cataclastic texture. Grain boundary alteration with development of calcite is prevalent.

In the northern limb of the fold, these last two units gradually thin and merge with the following to a massive granoblastic pyroxene-plagioclase rock.

Basic Granulite

Outcrop of this unit is poor. In the field it is difficult to decide whether it forms part of the metanorthosite or country rock, relation to the former being on microscopic features, particularly rutile exsolution in orthopyroxene. It is an orthopyroxene-clinopyroxene-plagioclase-garnet-opaque rock with great variation in mineral proportions, garnet and opaques varying from nil to twenty percent, at the same time changing from massive to well-layered. Although variable it is recognisable throughout the area. Contact with the outer massive metanorthosite is presumed sharp, the evidence being topographic expression. Contact with the quartzose granulite country rock is also not well exposed - near the first outcrop of quartz-rich rock, stringers of this material appear in the basic granulite as lenses elongate parallel to the layering, leading to the quartz-potash feldspar-garnet granulite country rock. This is taken as the outer contact of the metanorthosite massif for mapping purposes, and is interpreted as being hybrid, with the quartzose lenses representing deformed xenoliths.

Country Rock

Massive quartz-feldspar granulite surrounds the metanorthosite and is conformable with it. It is a medium-grained, quartz-potash feldspar ± garnet granulite, which is massive to one inch scale layered, with occasional half to one inch bands. The feldspar is markedly perthitic (up to thirty percent) and deformation is evidenced by the elongation and interlocking of all grains. Layered basic granulite occurs in this unit, but has been little investigated - the assemblage plagioclase-clinopyroxene-garnet-opaque is noted. Similar rocks occur in areas mapped to the west (A.D.T. Goode. pers. comm.).

Small Intrusive bodies

Dyke-like intrusions can be described in three groups.

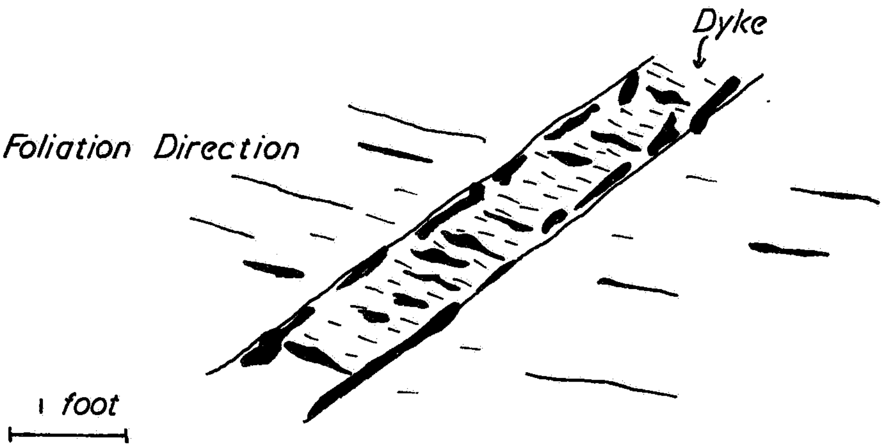
1. "metanorthositic dykes".
2. metamorphosed small basic dykes.
3. large foliated dykes.

These almost certainly have different ages.

1. "metanorthositic dykes".

In three places in the metanorthosite, dyke-like bodies were observed cross-cutting the foliation. These have the same mineralogy as the surrounding rock, but are slightly more mafic. The mafic mineral, probably orthopyroxene, is concentrated in a thin selvedge to the dyke and in lensoid masses (up to three inches long) parallel to the foliation of the enclosing rock, The dykes were therefore emplaced prior to foliation development and are evidence for an "anorthosite period of igneous activity".

FIGURE 3 : "METANORTHOSITIC DYKE" PLAN VIEW



In many other places large masses (up to one hundred by one hundred feet) of similar rock were observed, but contacts were either indefinite or obscured - these may be of similar origin.

2. Metamorphosed small basic dykes.

This group of dykes is generally fine-grained and recrystallised, only rarely showing remnants of chilled margins. They occur along fault zones (orientation approximating dip 50°N, strike 300°) and except in one case are not badly sheared by later movements. The map shows only a small number of larger dykes (up to ten feet wide), there being many others which give the area a streaked appearance on aerial photographs. They are mafic with pyroxene greater than fifty percent in all cases, almost reaching one hundred percent in one pyroxenitic rock. Textural variation is great, ranging from almost "igneous" with plagioclase laths and orthopyroxene phenocrysts in a granulated "groundmass" of ortho- and clinopyroxene, to completely granulated rock in which garnet has developed. These dykes are of extreme interest and selected examples will be described in greater detail in the section on metamorphism.

3. Foliated Dykes.

These prominent north-west trending dykes truncate the area in the east. Mineralogy is simple and homogeneous - plagioclase-orthopyroxene - and the texture cataclastic with bent and augen-shaped grains surrounded by finer granulated material and "pseudotachylite," this last forming a foliation of similar orientation to the dyke itself. Presumably the deformation producing this texture is related to movement along the fault plane intruded by the dyke.

Picrite Plug

A small picrite plug intrudes the metanorthosite, cross-cutting a dyke of the type described in 2. Slight chilling and hybridisation of metanorthosite and picrite are found at the contacts. The rock, which is undeformed, shows a beautiful igneous texture in thin section, which can only be briefly and inadequately described. The mineral assemblage is olivine-spinel-clinopyroxene-orthopyroxene-hornblende-plagioclase-biotite associated in many textural relationships.

Petrologic descriptions of most of the above rock types are given in Appendix II. Their distribution is shown on the geological map (regional geology after Mirams [1964]).

GEOCHEMISTRY AND MINERALOGY

Geochemical work was undertaken on material from Teizi for several reasons-to use geochemical evidence to help elucidate the history of the metanorthosite, to obtain needed data on anorthosites and to familiarise the author with geochemical methods. Since the metanorthosite consists of a related sequence of rock types, samples were collected as systematically as possible across the strike in order to reveal any geochemical trends. Ten specimens were prepared for analysis - whole rock and separated plagioclase - as noted in Appendix I. Sample locations can be found on the geological map.

The sample numbers and corresponding lithologic units are:

A298 - 142	Core gabbroic metanorthosite
196	Core massive metanorthosite
110	Core blue metanorthosite
119B	Inner layered unit
119D	Inner layered unit
120	Outer blue metanorthosite
126	Outer layered unit
117	Outer massive metanorthosite
48	Garnet-bearing metamorphosed dyke
194	Metamorphosed dyke

The investigations used for comparison are whole rock and trace element analyses of Canadian anorthositic rocks (Papzik 1965; Philpotts, 1966) and data on the Giles Complex from various sources.

TABLE 1

Feldspar	142	196	110	119B	119D	120	126	117*	48	194
Na_2O%	5.32	5.09	4.75	4.48	4.76	5.15	5.81	5.03	5.26	4.65
K_2O%	.81	.69	.68	.24	.32	.57	.71	.87	.19	1.69
CaO%	9.98	9.96	10.87	11.75	11.46	10.85	9.43	9.55	10.50	10.22
An% wt?	49.7	51.0	54.8	59.3	57.0	53.2	46.5	49.7	52.9	51.0
Ab%	46.2	45.4	41.7	39.4	41.3	44.0	49.9	45.7	46.2	40.4
Or%	4.1	3.6	3.5	1.2	1.6	2.9	3.6	4.7	1.0	8.6
Partial Analysis	99.4	96.5	98.1	97.6	99.0	100.8	100.2	95.1	97.7	100.0
$\frac{An}{An + Ab}$	51.8	52.9	56.8	60.0	58.0	54.7	48.2	52.1	53.4	55.8
Sr ppm.	1400	1400	1350	880	700	1640	1370	1380	1220	1420
Mol % An	48.61	49.91	53.70	58.36	55.92	52.13	45.46	48.62		

* Due to incomplete digestion this analysis in low in calcium.

FIGURE 4 : PLAGIOCLASE VARIATION

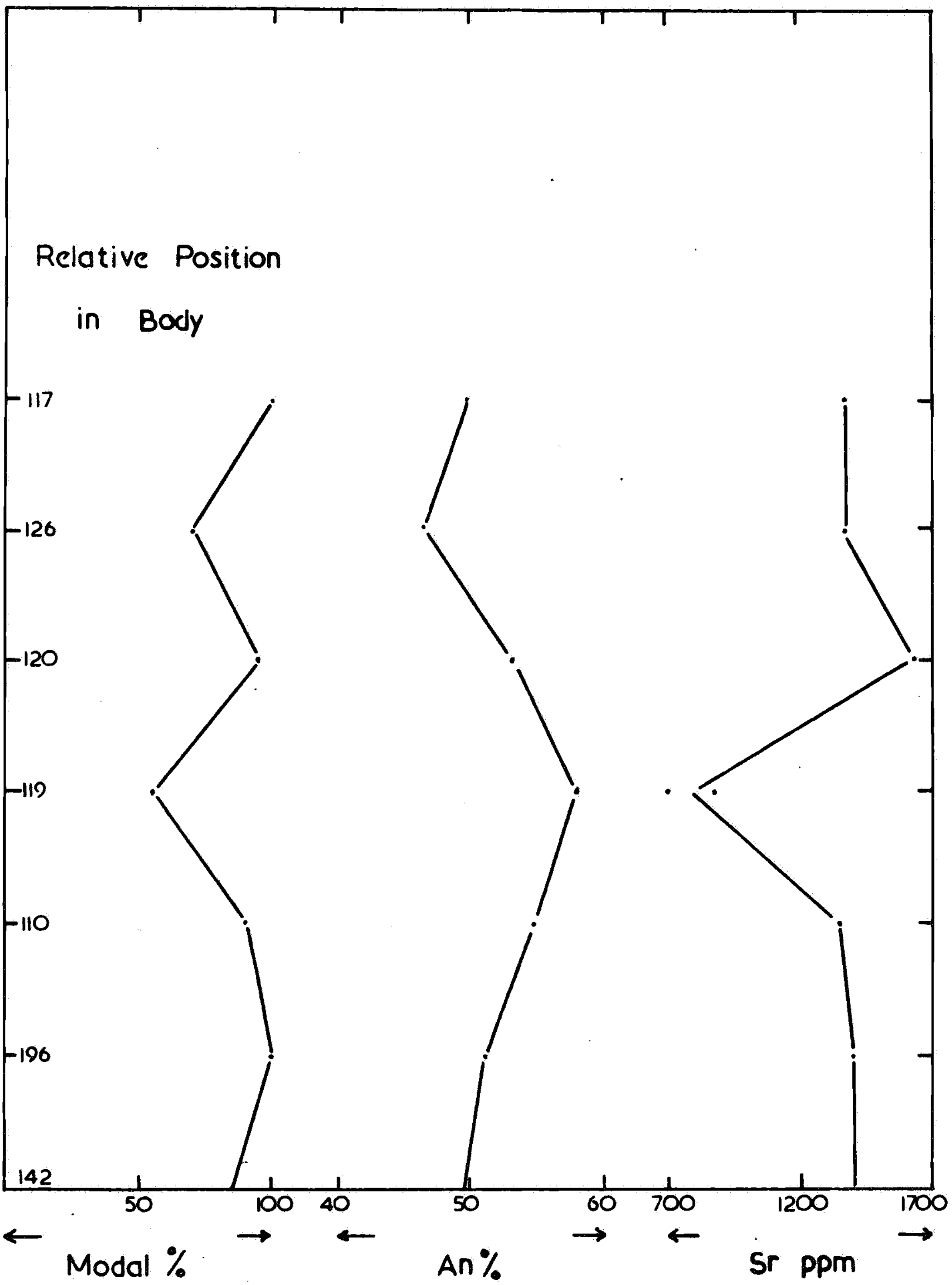
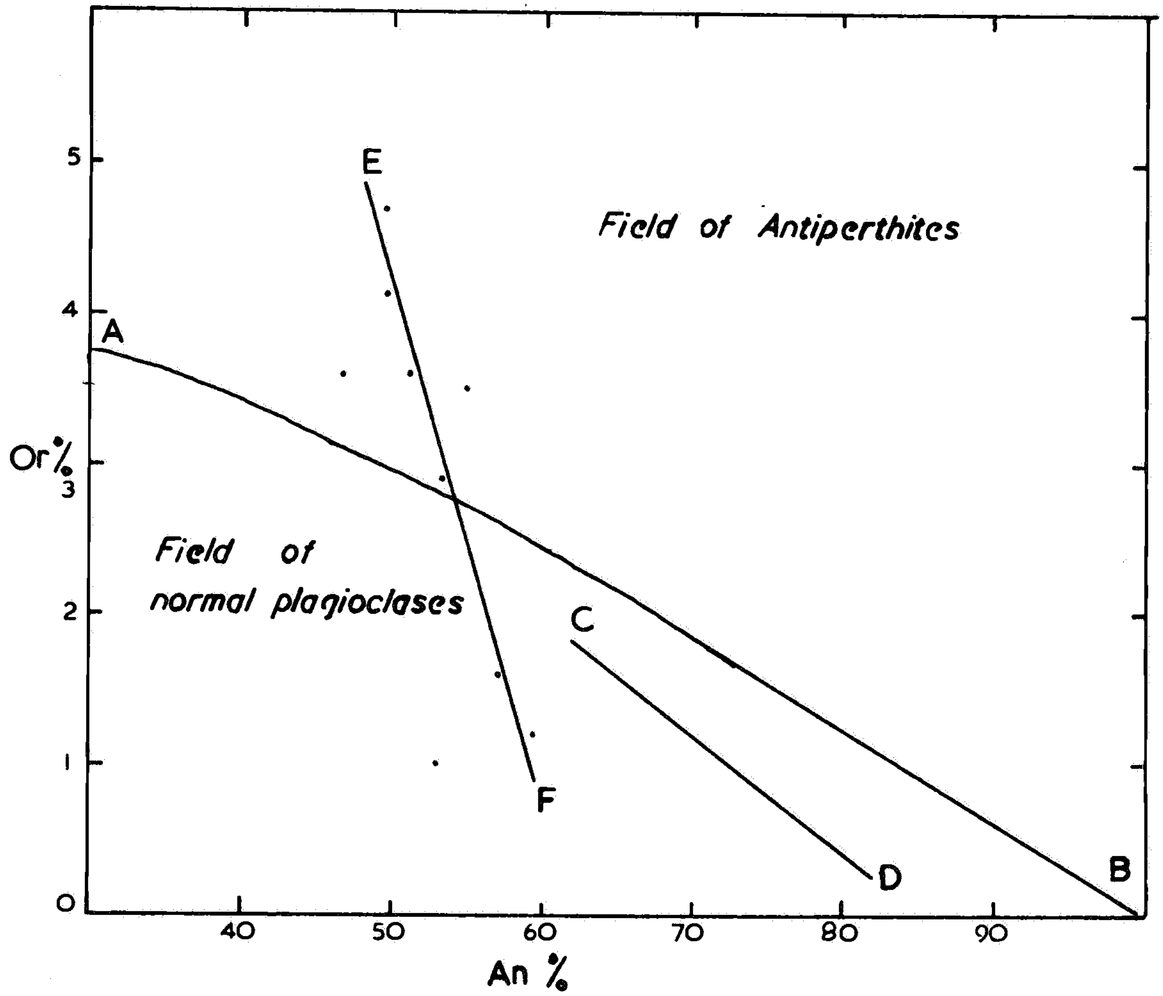


FIGURE 5 : PLAGIOCLASE OR% VERSUS AN%



AB Limit of normal plagioclases after Smith and Emmons.

CD Mt. Davies plagioclases after Kleeman.

EF Teizi Metanorthosite Plagioclases.

Plagioclase Geochemistry

a. Analysis

Partial analyses for sodium, potassium and calcium are tabulated in Table 1, along with calculated analysis percent and feldspar end member content. (Methods of analysis are given in Appendix I).

The variation in feldspar composition across the body is shown in figure 4 along with modal plagioclase percent.

Since a number of the feldspars are antiperthitic, the relation of potassium to sodium and calcium is of interest. Because of its chemical similarity to sodium, potassium would be expected to show a positive correlation with this element and conversely a negative relation to calcium. A plot (fig. 5) of Or% versus An% (An% to allow comparison with other work) reveals the expected correlation in a linear fashion. Feldspar 194 (Or = 8.6), from a dyke rock, is the only divergent example and its high potassium content may be due to contamination. The country rock outside the metanorthosite contains much potash feldspar which would provide the potassium - however, its associated rubidium was not detected, suggesting that this is an original feature. The substitution of potassium for sodium in plagioclase depends on the interaction of temperature, pressure, availability of potassium and plagioclase composition. The linear Na-K relationship indicates that the first three factors were in balance for all rock types, a feature, which particularly for the case of availability, is only attained by liquid-crystal equilibrium.

At lower pressures and temperatures than those of formation, plagioclase can hold less potassium in its lattice and may unmix potash feldspar if potassium is above the tolerance level for the physical conditions. Samples 119B and 119D are not antiperthitic, while 120 is, indicating that the critical Or content is between 1.6% (119D) and 2.9% (120). Comparison with the Mt. Davies feldspars (not antiperthites) and those quoted by Smith reference and Emmons (antiperthites excluded) defines the critical boundary quite precisely for varying plagioclase composition. Note that antiperthitic feldspars should delimit the boundary, as some high potassium examples may not show exsolution simply because conditions suitable for nucleation of the exsolved phase have not been attained.

The strontium content of the plagioclases is given in Table 1. Strontium commonly shows a negative geochemical relation to calcium. Linear trends of increasing strontium with decreasing calcium in the differentiation sequence of basic intrusions are often found (e.g. Kleeman, 1965). Such a trend is suggested in Fig. 6, but is not well developed. Fig. 4 shows that strontium reflects the geochemical break at the inner layered unit (119).

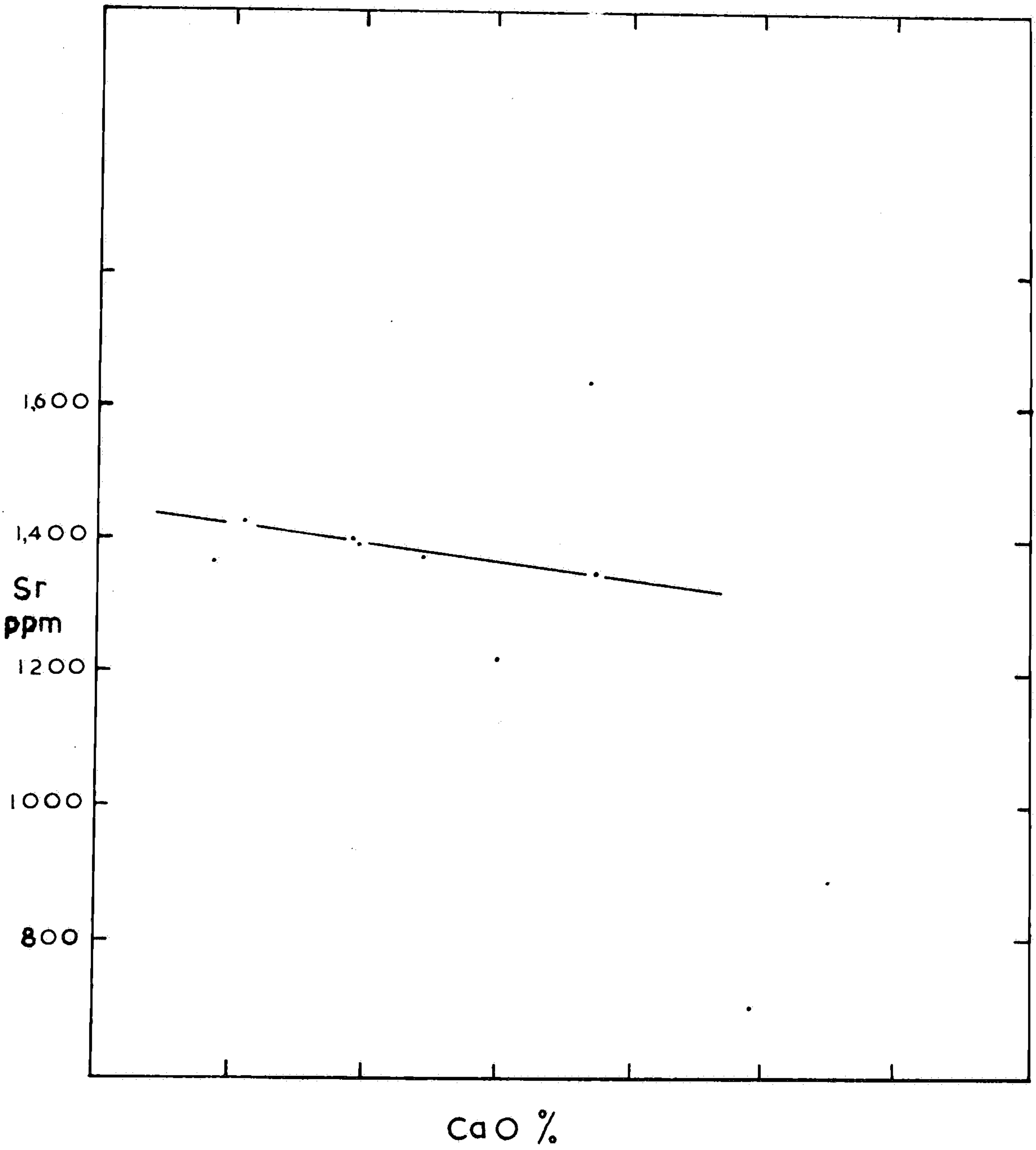
Rubidium was not detected in these feldspars.

b. <u>Exsolution in Plagioclase</u>

1. Antiperthite

Potash feldspar occurs in the plagioclase as small, square, wedge or elongate grains with parallelism of any long axis.

FIGURE 6 : PLAGIOCLASE Sr ppm Vs CaO %



They usually occur along twin lamella boundaries or fractures, but sometimes in apparently untwinned grains, perhaps related to submicroscopic twinning. Following Carstens (1967) it is concluded that these result from continuous precipitation with nucleation along twin boundaries which are energetically favourable due to high concentration of dislocations. In alloy systems unmixing post-dates twinning, so that exsolution in the Teizi plagioclase occurred after the formation of deformational twins which are presumably related to the large scale folding of the area.

not necessary

post-dates PRIMARY twinning in alloy systems but may (& probably does) pre-date SECONDARY twinning.

2. Opaque Inclusions

In common with other anorthositic bodies the plagioclases contain many opaque, oriented inclusions in the form of euhedral rods, which may occur singly or in trains with twenty or more individuals. The inclusions are probably haematite or ilmenite and have resulted from exsolution, ferric iron being rejected from aluminium sites on cooling.

c. Diffractometry

The intention of this work was to determine the structural state of the suite of plagioclases and if possible to derive a composition calibration. The parameters investigated were:

$\Gamma = 2\theta\,(131) + 2\theta\,(220) - 4\theta\,(1\bar{3}1)$ Oscillation = $28 - 32^\circ 2\theta$

$B = 2\theta\,(1\bar{1}1) - 2\theta\,(20\bar{1})$ " = $21.5 - 23.5^\circ 2\theta$

The results are shown in Table 2.

TABLE 2

Γ and B values with standard deviation.

Sample Number wt% An %	Γ	B	An/An+Ab
142 49.7	.609 ± .018	.868 ± .007	51.8
196 51.0	.631 ± .026 .639 ± .039 } Av. .635	.867 ± .007	52.9
110 54.8	.717 ± .009	.856 ± .005	56.8
119B 59.3	.848 ± .012	.839 ± .011	60.0
119D 57.6	.764 ± .011	.849 ± .006	58.0
120 53.2	.633 ± .009	.863 ± .008	54.7
126 46.5	.585 ± .016	.878 ± .011	48.2
117	.650 ± .023	.863 ± .012	52.1
48	.776 ± .026	.846 ± .004	53.4
194	.792 ± .013	*	55.8

* unable to determine satisfactorily.

As can be seen in figure 7, Γ and B versus anorthite percent, B gives a smooth curve, while Γ is marked by greater scatter This is reduced when the ordinate is $\frac{An}{An + Ab}$, removing the effect of potassium on feldspar composition, the points being described by two straight lines (fig. 8). (Note that the composition of 117 is uncertain and should be more calcic). Previous work shows the presence of an inflection point in the region of An_{50} and this has been found here. It unfortunately reduces the usefulness of the curves in composition determination because of the small change in the diffraction parameter with composition.

Experimental determination of the Γ parameter proved difficult. Initial runs on hand ground powders produced great internal variation in results. After unsatisfactory trials on a known feldspar, using powders hand-crushed (usual procedure) for periods up to ten minutes, mechanical crushing (half hour) was used, giving good precision (see standard deviation) for a number of samples. Even so, some poor results were obtained, indicating that grain size was not the only problem. Two possible explanations for the unsuitability of Γ are:

1. Structural changes in this composition range having very sensitive manifestation in d spacings requiring great randomness of particle orientation and consequent reduction in grain size.

2. The antiperthitic nature of many of the samples.

Precision of B measurement was always good leading to the conclusion that it is a superior parameter for compositions near An

FIGURE 7 : Γ AND B VERSUS AN %

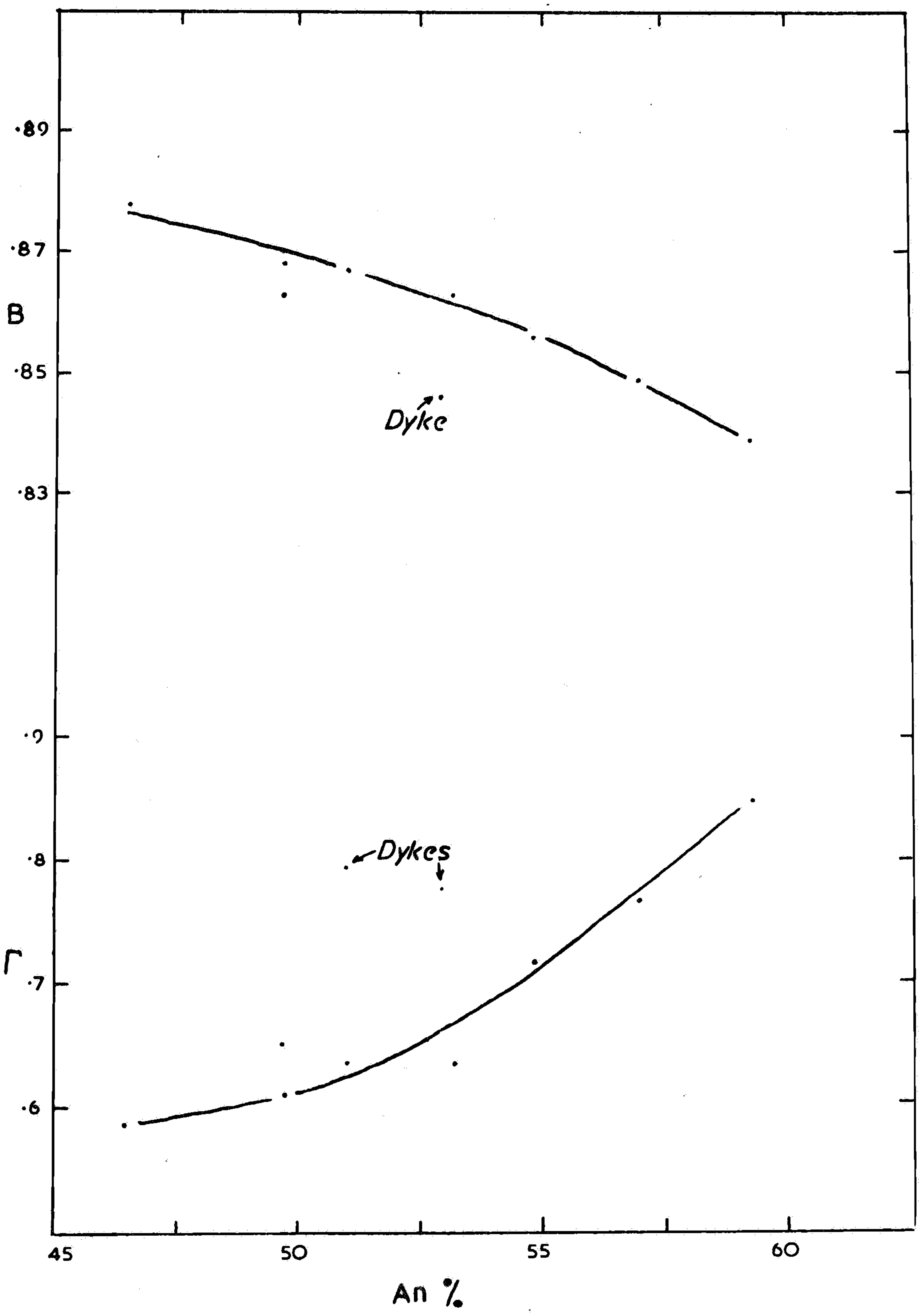


FIGURE 8 : Γ AND B VERSUS $\frac{AN}{AN + AB}$

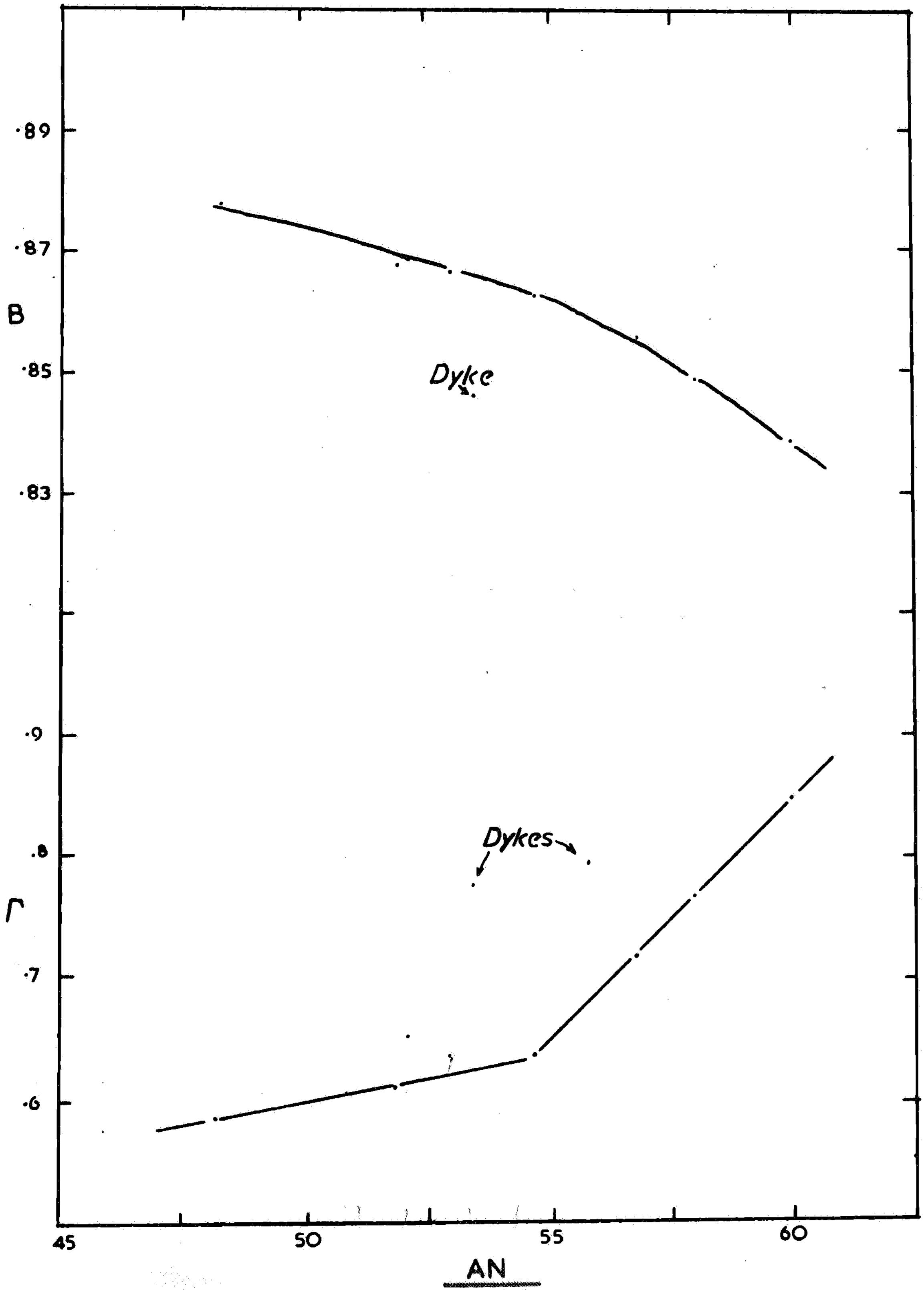
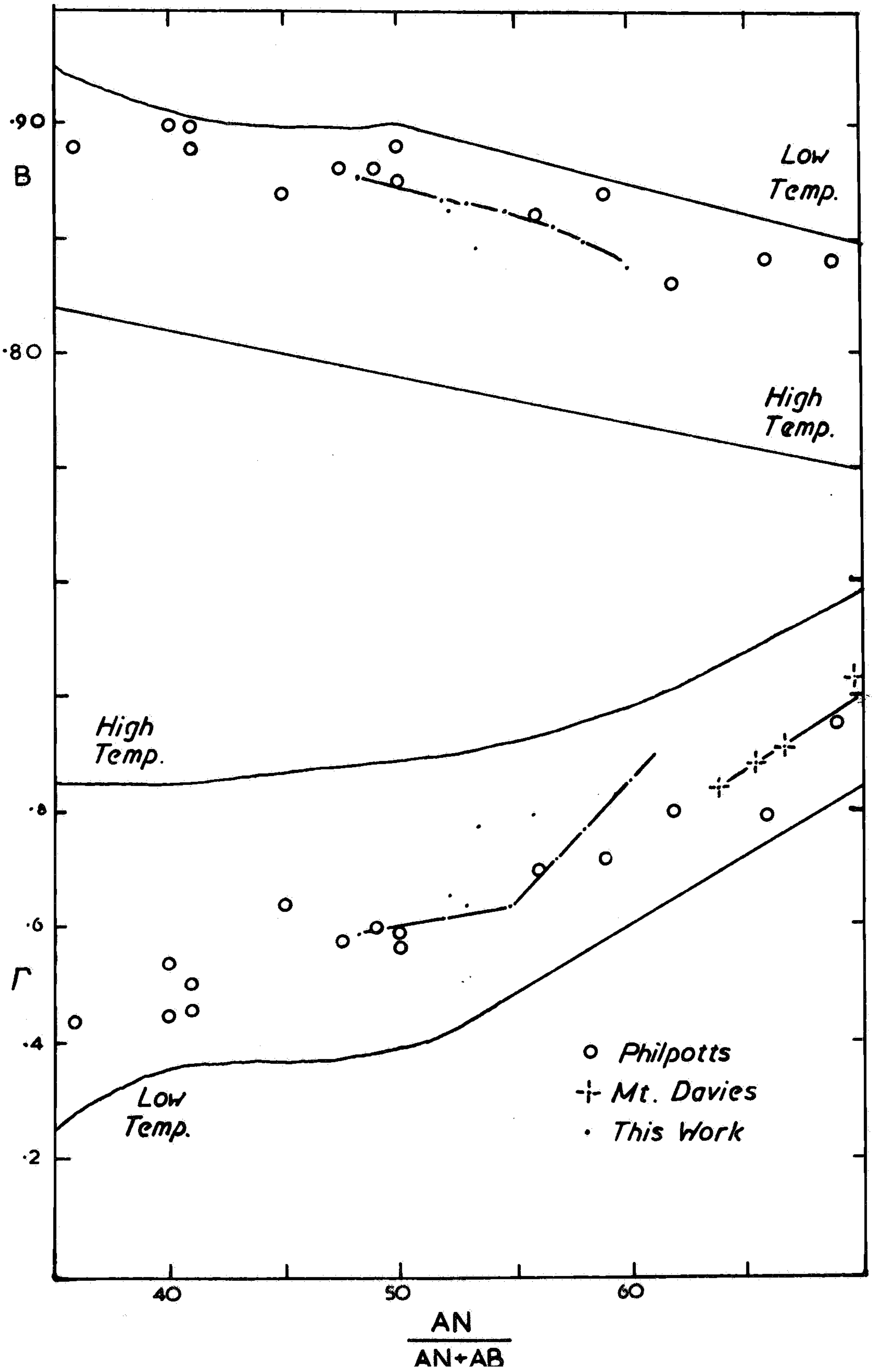


FIGURE 9 : Γ AND B – COMPARISON WITH OTHER WORK



Structural State

The Teizi plagioclases form a coherent group with a low transitional structural state similar to that found in other high grade metamorphic terrains and layered intrusions. Comparison (Fig. 9) is made with Philpotts (1966), Kleeman (1965) and the low and high temperature structural state curves, indicating similar structural state to that of the Canadian anorthositic rocks, but perhaps slightly higher than that in the Mt. Davies Intrusion. The feldspars from the metamorphosed dykes have a much higher structural state indicating a different thermal history, probably related to rapid cooling on intrusion with preservation of the higher temperature structural state. Recrystallisation accompanying granulite facies metamorphism has apparently not affected the structural state indicating sluggishness of change.

Pyroxene Mineralogy

No quantitative work was done on the pyroxenes of the area, this discussion being restricted to some important qualitative observations.

The predominant pyroxene of the metanorthosite is a pleochroic orthopyroxene, clinopyroxene being limited to accessory status except in the inner layered unit. The dykes contain orthopyroxene as relic phenocrysts and orthopyroxene and clinopyroxene as "groundmass".

Composition

As the FeO:MgO ratio of the rocks is constant (see rock geochemitry), orthopyroxene composition in the metanorthosite is constant - it is a bronzite (optically negative). Orthopyroxene also occurs in the metamorphosed dykes (optically positive) and foliated dykes (appears to be optically negative).

Pegmatite

Orthopyroxene crystals attain large dimensions (up to ten inches) in occasional pegmatitic areas of the blue metanorthosites. The large crystals, apart from containing much plagioclase and lesser clinopyroxene as sheets in the XY optic plane are similar to their smaller counterparts.

Rutile Exsolution

Rutile exsolution is almost ubiquitous in the orthopyroxene of the metanorthosite and crosscutting dykes. Rutile needles are found in the (010) planes of the pyroxene, oriented parallel to $(\bar{6}01)$, (601) and (001) (A.C. Moore, in press). This phenomenon has not been reported outside the Giles Complex. It has been studied in detail by A.C. Moore, who identified the needles using an electron microprobe. He concludes that this form of exsolution has taken place because of excessive substitution of titanium in ferrous iron and magnesium sites at high pressure.

In the metamorphosed dykes (small intrusives 2) exsolution has only been found in relic phenocrysts, the granular orthopyroxene showing none.

Ilmenite and plagioclase inclusions.

Philpotts (1966) reported plagioclase and ilmenite of similar orientation as inclusions in clinopyroxene. A similar feature is found in some clinopyroxenes of the inner layered unit, where the opaque consists of an exsolution intergrowth of haematite and ilmenite. It is suggested that the haematite - ilmenite intergrowth exsolved from the pyroxene, but that the plagioclase represents inclusions because of (1) the plagioclase extends to the edge of the pyroxene grains in some cases and (2) plagioclase only occurs in a few grains per slide.

WHOLE ROCK GEOCHEMISTRY

Whole rock analysis

Whole rock analyses were made of nine samples by means of wet chemistry and X-ray fluorescence spectrography, (see Appendix I). The analyses are shown in Table 3. The totals show great variation and although the reason for this is unknown, it is hoped that the results may be used in a relative fashion.

A number of interesting geochemical relations can be derived from this data.

FeO - MgO (Figure 10).

Figure 10 shows a linear relationship between ferrous iron and magnesium for the metanorthosite rocks. Since the graph passes through the origin, FeO/MgO is constant and as orthopyroxene (Mg,Fe)SiO_3 is the only major iron and magnesium bearing mineral in these rocks, it may be inferred that the orthopyroxene composition is constant. 119B has the mineral assemblage garnet-clinopyroxene-plagioclase, but plots on this line suggesting that the garnet and clinopyroxene formed from an orthopyroxene-plagioclase association without change in the amount of ferrous iron. The dykes 48 and 194 have a different FeO/MgO.

By comparison a plot of Mt. Davies analyses shows a marked linear trend and a region of scatter. The linear trend is shown by rocks of the "critical zone" where anorthosite is developed.

FeO - MnO (Figure 11).

A linear correlation of these elements is found regardless

TABLE 3. Whole Rock Analyses

	142	196	110	119B	119D	120	126	48	194
SiO_2	54.19	56.24	53.90	50.45	51.86	56.96	55.21	46.19	53.02
TiO_2	.22	.12	.17	.39	.48	.15	.20	.64	.92
Al_2O_3	22.15	27.81	25.99	24.87	21.36	28.11	20.27	15.59	12.76
Fe_2O_3	.57	.66	.74	.57	2.38	.56	.63	1.53	2.39
FeO	4.11	.35	2.36	4.94	3.84	1.03	5.99	9.46	8.75
MnO	.08	.03	.05	.11	.09	.04	.10	.14	.16
MgO	4.12	.19	2.06	4.40	6.77	.93	5.43	11.52	11.02
CaO	8.53	10.14	10.04	12.86	12.16	10.11	6.25	10.70	9.20
Na_2O	4.16	4.88	4.08	3.89	3.08	4.91	3.93	2.64	2.80
K_2O	.44	.77	.45	.20	.12	.35	.30	.09	.81
P_2O_5	.01	nil	.01	tr	.01	.01	tr	.03	.11
Total	98.59	101.18	99.85	102.68	102.15	103.16	98.31	98.53	101.94
Sr ppm	800	930	890	430	650	1120	700	220	200

FIGURE 10 : FeO % VERSUS MgO %

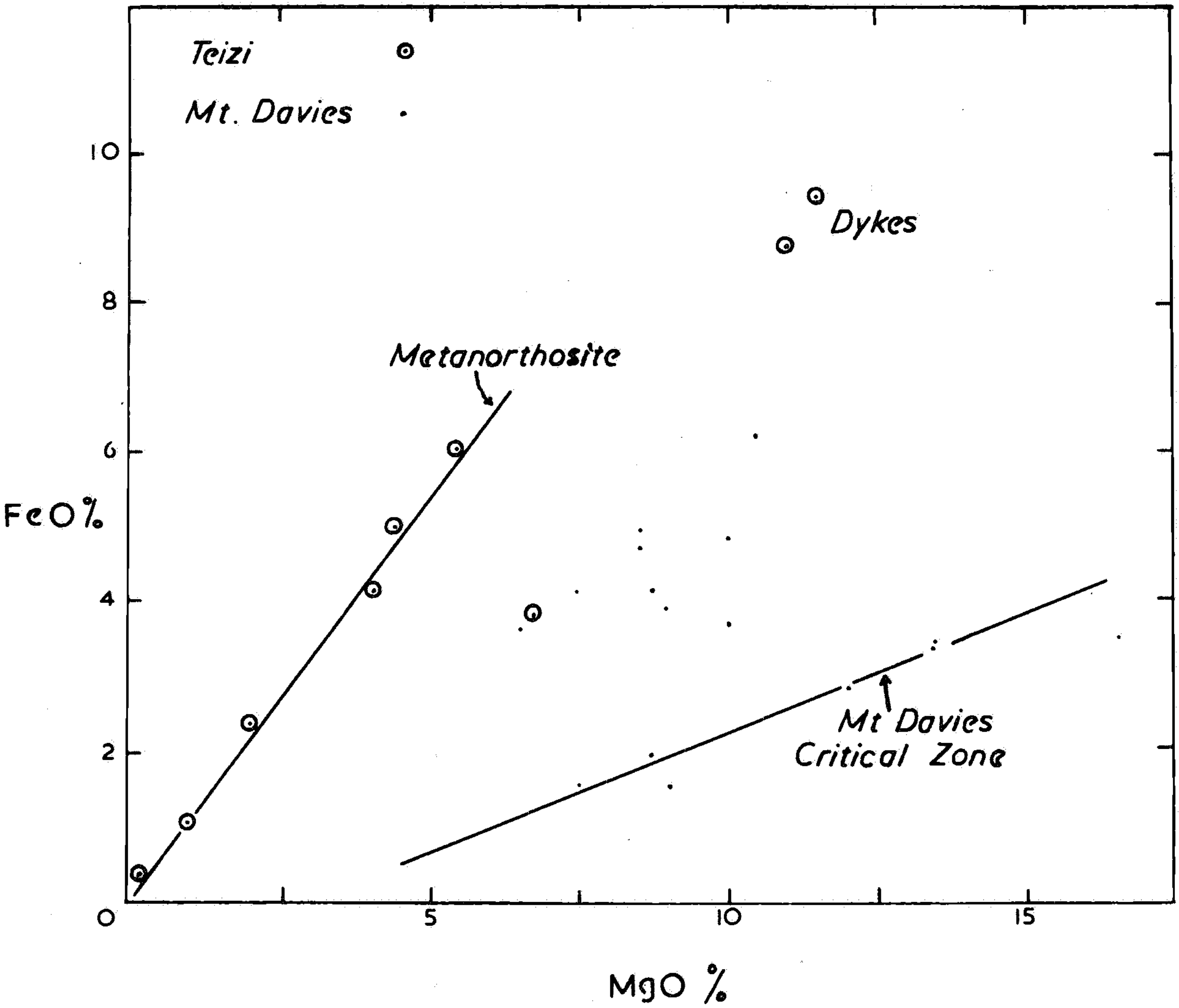
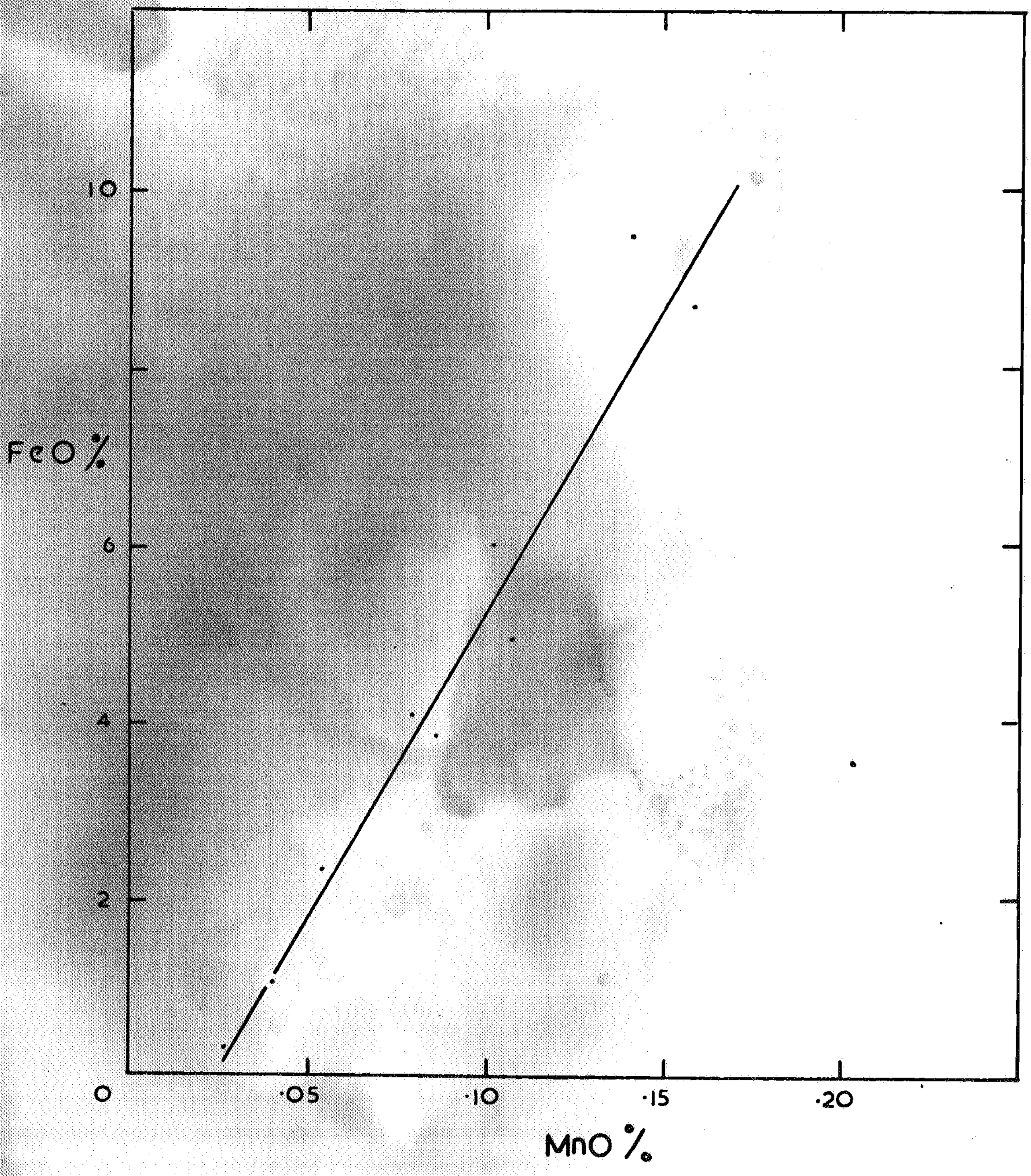


FIGURE 11 : FeO % VERSUS MnO %



of manganese in ferrous sites of orthopyroxene, clinopyroxene and garnet.

$MgO - TiO_2$ (Figure 12).

Another linear relation is shown in this plot. Titanium is located in three places in these rocks (1) ilmenite - which in some cases is exsolved from clinopyroxene (2) rutile exsolution in orthopyroxene (3) substitution in pyroxene. Since most titanium seems to have been derived from lattice sites in the pyroxenes, it is not surprising that correlation is found with a similar element in these minerals, in this case magnesium. Those rocks with clinopyroxene show a higher content of titanium indicating greater substitution in the magnesium sites of this mineral.

$K_2O - Na_2O$ (Figure 13).

The whole rocks show a trend of increasing potassium with sodium in a similar fashion to that discussed for the plagioclases in which phase these elements are restricted.

FIGURE 12 : MgO VERSUS TiO_2

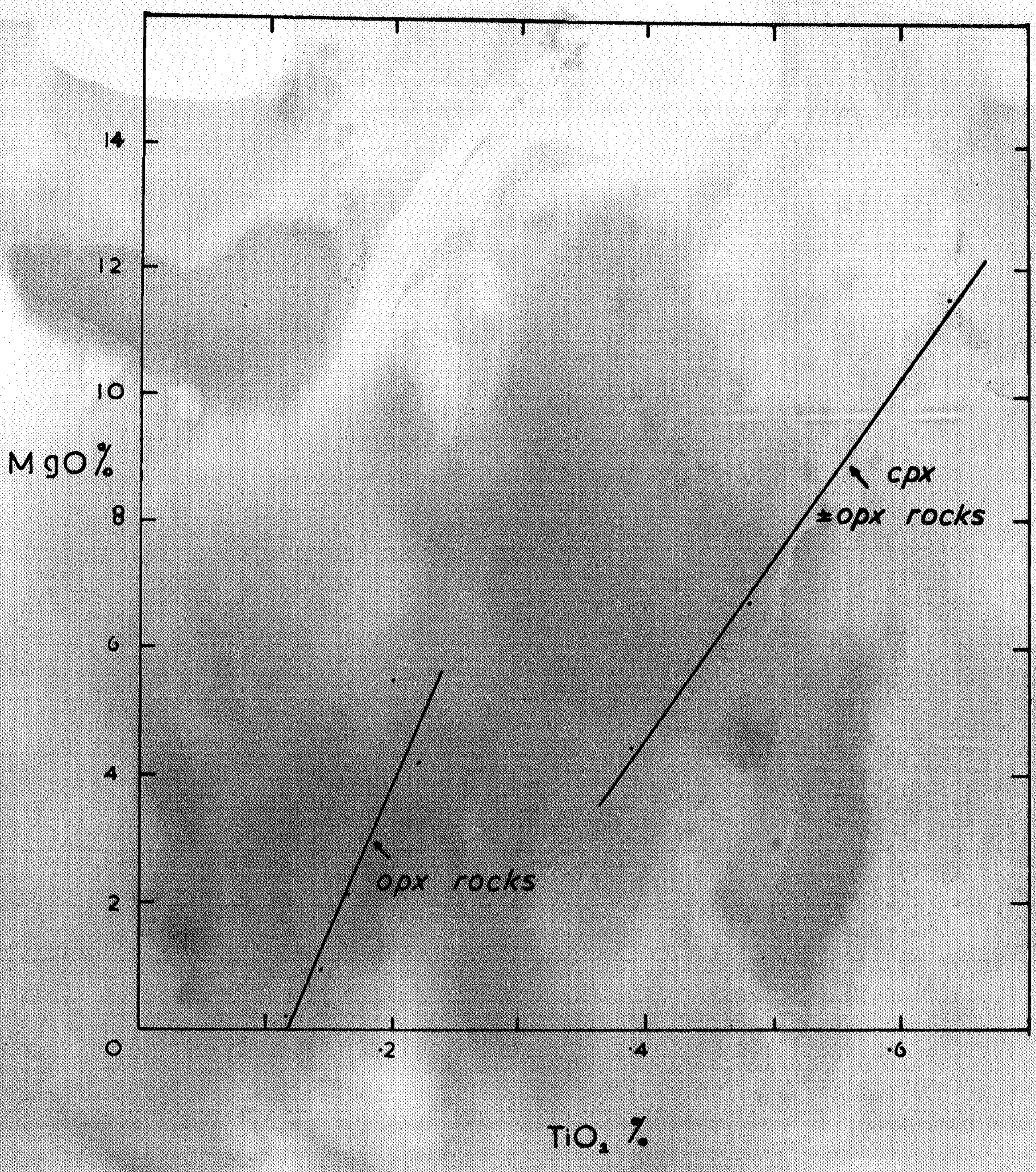
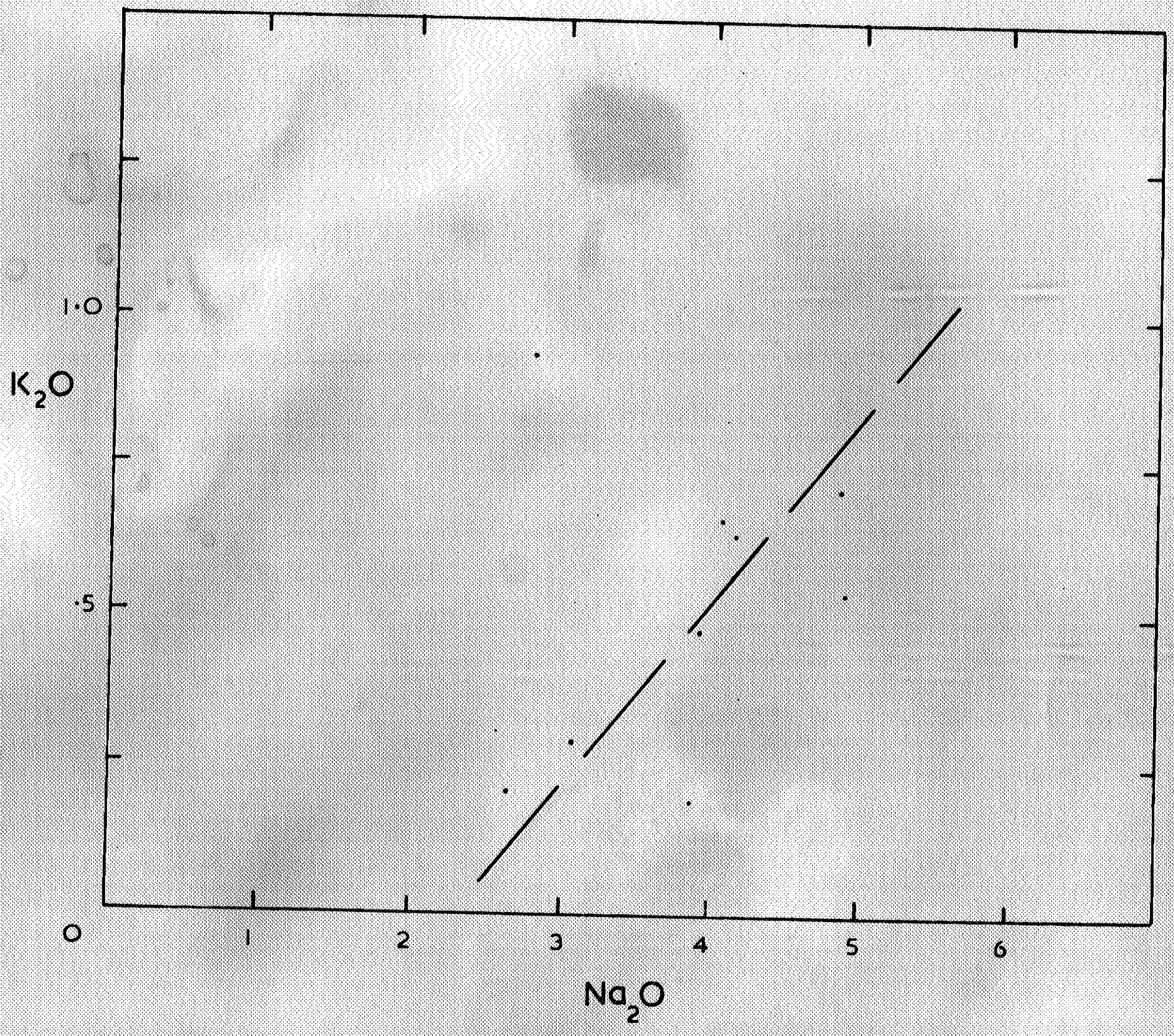


FIGURE 13 : K_2O VERSUS Na_2O



METAMORPHISM

The metamorphism of the Teizi Metanorthosite is conveniently considered in two sections (1) the rocks related to the metanorthosite and (2) the crosscutting dykes, both of which show granulite facies mineral assemblages.

Metanorthosite Metamorphism

The mineral assemblages found in the metanorthosite are: plagioclase, orthopyroxene - plagioclase, orthopyroxene - clinopyroxene - plagioclase, orthopyroxene - clinopyroxene - plagioclase - hornblende, orthopyroxene - clinopyroxene - garnet, orthopyroxene- clinopyroxene - garnet - plagioclase - opaque. Metamorphism is evidenced by recrystallisation, formation of garnet and reaction textures. The assemblage plagioclase ± orthopyroxene is stable in most rocks, but those with suitable compositions show varying degrees of reaction in the form;

orthopyroxene + plagioclase $\rightleftharpoons$ clinopyroxene + garnet + quartz (1

A rock in the basic granulite unit (A298-186) shows the reaction in an arrested state, with various well-developed rims of reaction products. Orthopyroxene occurs as irregular, severely altered grains with garnet and opaque rims and embayments. Garnet rims form between plagioclase and opaque, narrow quartz rims between orthopyroxene and opaque, plagioclase and garnet. Clinopyroxene is found as grains lateral to orthopyroxene and as stringers in garnet.

Reactions taking place are:

plagioclase + opaque $\rightleftharpoons$ garnet

The inner layered unit shows this latter reaction at completion, with the formation of garnet-clinopyroxene (small scale) and garnet-clinopyroxene-plagioclase assemblages and attainment of textural equilibrium. Small spinel centres to some garnet grains suggests that the reaction may have been:

spinel + plagioclase + orthopyroxene $\rightleftharpoons$ garnet.

Metamorphosed Dykes

As previously described, the dykes vary from partly to completely recrystallised and metamorphosed. The mineral assemblages are:

orthopyroxene - clinopyroxene - hornblende - plagioclase, orthopyroxene - clinopyroxene - plagioclase, orthopyroxene - clinopyroxene - plagioclase - spinel, garnet - clinopyroxene - plagioclase.

Rimming textures are uncommon, but show orthopyroxene phenocrysts surrounded by garnet which contains occasional stringers of quartz (A298-49). With further reaction the rock is converted to a granoblastic aggregate of subhedral garnet, clinopyroxene and plagioclase (A298-48), i.e. the reaction again is (1). It can be seen then, that both the metanorthosite and dykes are at the same grade of metamorphism.

A pyroxenitic dyke (A298-100) contains the unusual assemblage orthopyroxene-clinopyroxene-biotite-garnet-spinel-plagioclase. Perfect garnet rims enclose the spinel and much of the biotite. The interpreted reaction in this case is,

spinel + pyroxene + potassium + water $\rightleftharpoons$ garnet + biotite

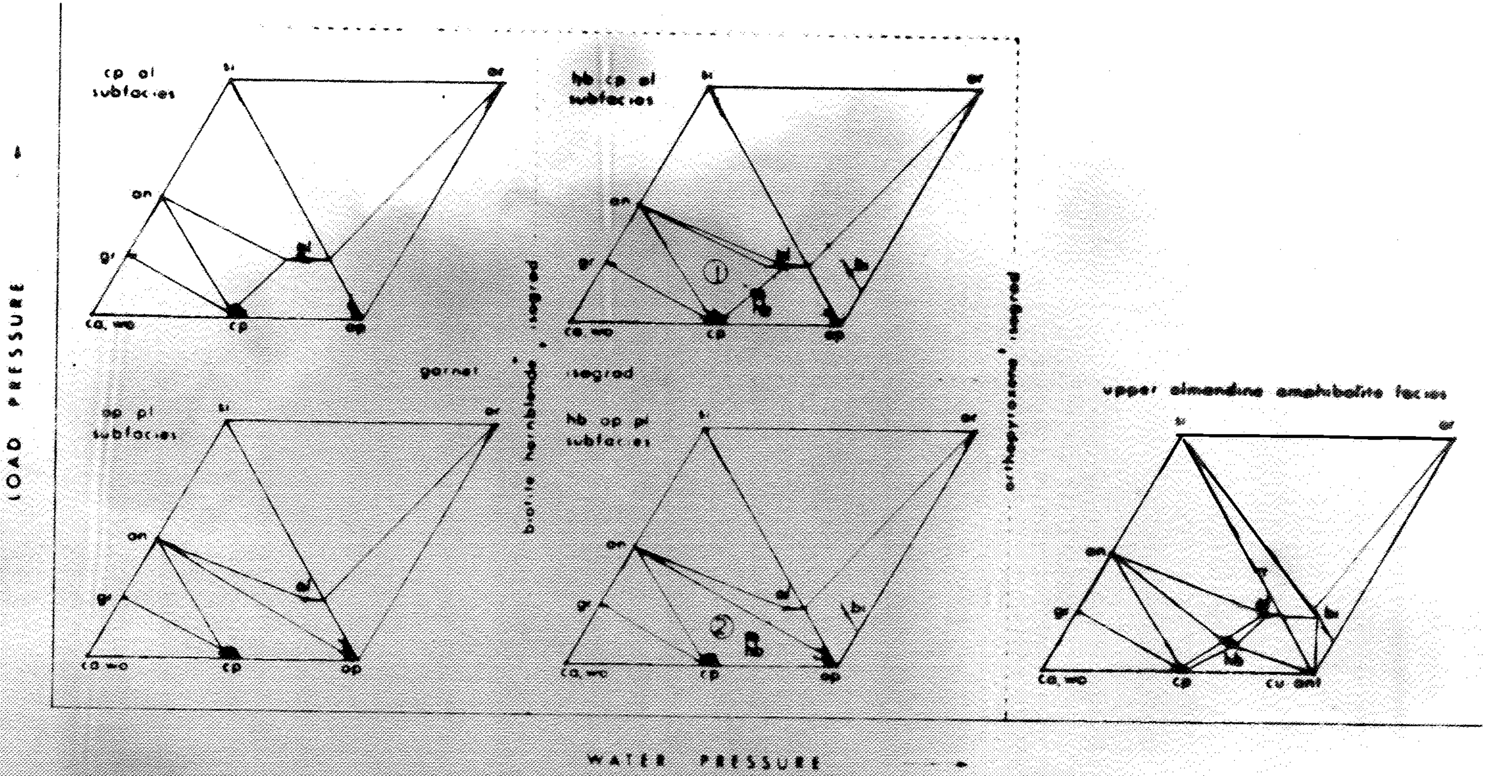


FIGURE 14 : CLASSIFICATION OF THE GRANULITE FACIES — DE WAARD (1965). ① = 48 . 1198 ② = 194 . 119D

The presence of spinel in some plagioclases also seems to be due to metamorphism.

Classification of Metamorphic Grade

The granulite facies is defined by the appearance of hypersthene with increasing grade of metamorphism, by means of reactions such as:

$$\text{hornblende} + \text{quartz} + \text{biotite} \rightleftharpoons \text{orthopyroxene} + \text{plagioclase} + \text{water}$$

Further subdivision of the facies has been proposed by several authors, the most complete being that of de Waard (1965), involving differences in P_{H_2O} and P_{load} and garnet and biotite - hornblende isograds - see Fig. 14. This results in four subfacies, those at higher P_{load} being introduced by the reaction (1).

As noted before, assemblages in the Teizi area consist of:

plagioclase - clinopyroxene - garnet = clinopyroxene - almandine or more likely hornblende - clinopyroxene - almandine subfacies (48 or 119B).

orthopyroxene - clinopyroxene - plagioclase ± hornblende = hornblende - orthopyroxene - plagioclase sub-facies (194 or 119D),

and can be assigned to two different subfacies. Since the grade of metamorphism over such short distances would be constant, it is evident that the formation of garnet in basic rocks is not a reliable indicator of grade.

Green and Ringwood (1967), using the results of their expossible.

Briefly it is:

Low Pressure: olivine + plagioclase

Intermediate Pressure: orthopyroxene + plagioclase (pyroxene granulite)

High Pressure: garnet + clinopyroxene + quartz (garnet granulite)

The pyroxene granulite - garnet granulite transition occurs by means of reaction (1). Experimentally it was found that bulk composition of a rock significantly influenced the physical conditions at which the reaction took place (see Fig. 15). As a result clinopyroxene - garnet - plagioclase and orthopyroxene - clinopyroxene - plagioclase assemblages can be stable at the same temperature and pressure in rocks of suitable composition.

The important chemical effects are:

1. the higher the silica content of a rock, the higher the pressure required to produce garnet, and
2. the higher the FeO/MgO, the smaller the pressure needed to give garnet.

These two points can be used to explain the mineralogical differences in the Teizi rocks.

(a) Inner Layered Unit.

119B cpx - ga - plag SiO_2 = 50.45% FeO/MgO = 1.12

119D cpx - opx - plag " = 51.86% " = .57

In terms of composition, 119B is favoured to produce garnet by a slightly smaller silica percentage and much larger iron-magnesium ratio.

FIGURE 15 : MINERAL ASSEMBLAGES OF VARIOUS BASALTIC COMPOSITIONS AS A FUNCTION OF PRESSURE AT 1,100°C — AFTER RINGWOOD AND GREEN (1966). NOTE COMPOSITIONS SIMILAR TO TEIZI ROCKS.

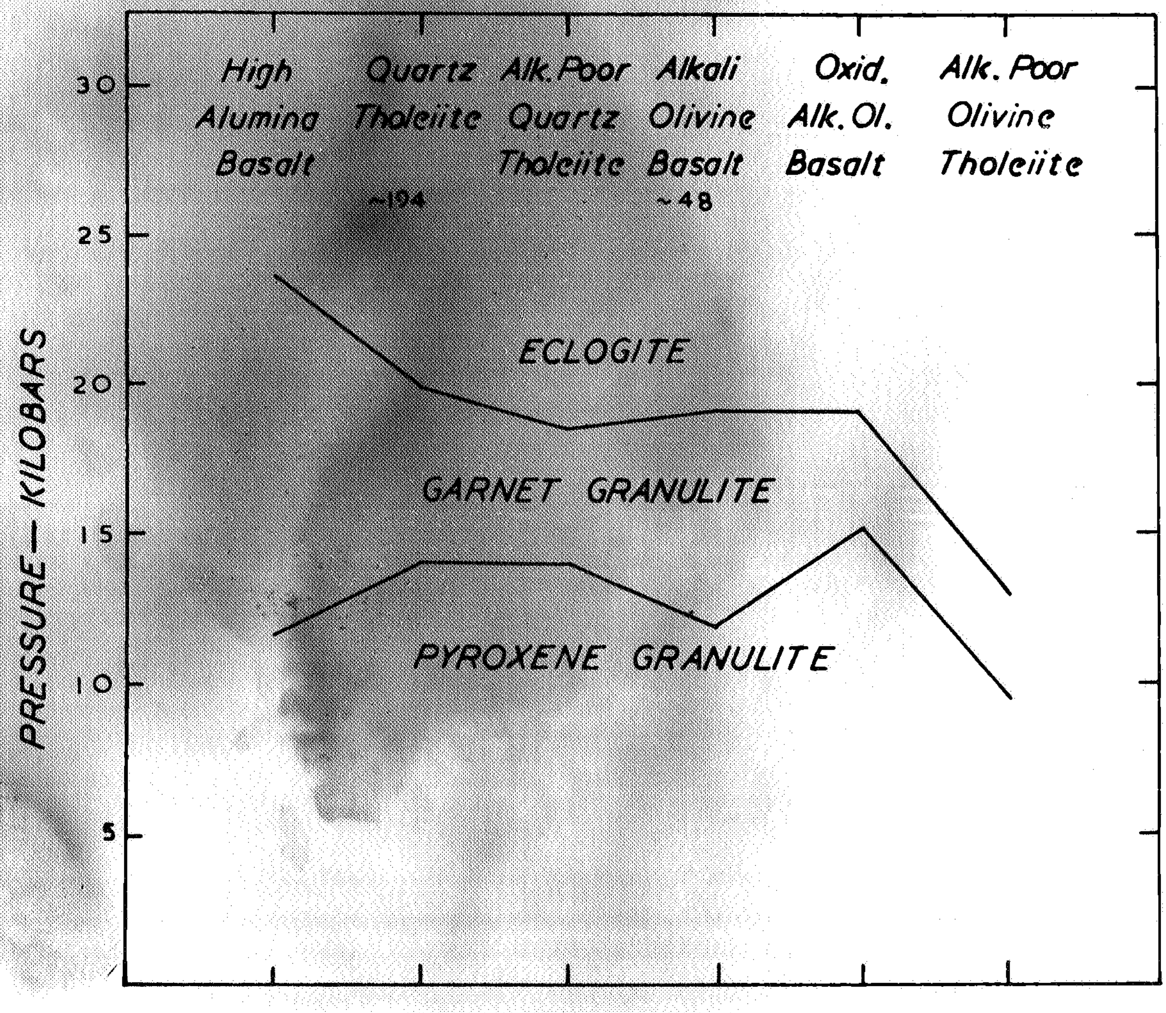


TABLE 4

Comparison of the composition of metabasites from the Teizi Metanorthosite with the experimental compositions of Ringwood and Green (1966).

	A298-48	≈	olivine tholeiite A.	A298-194	≈	quartz tholeiite B
SiO_2	46.19		46.93	53.02		52.16
TiO_2	.84		2.02	.92		1.86
Al_2O_3	15.59		13.08	12.76		14.60
Fe_2O_3O	1.53		1.02	2.39		2.46
FeO	9.46		10.07	8.75		8.39
MnO	.14		.15	.16		.14
MgO	11.52		14.55	11.02		7.36
CaO	10.70		10.16	9.20		9.44
Na_2O	2.64		1.73	2.80		2.68
K_2O	.09		.08	.81		.73
P_2O_5	.03		.21	.11		.18

(b) Metamorphosed Dykes.

48	cpx - ga - plag	SiO_2 = 46.19%	FeO/MgO = .82
194	cpx - opx - plag	" = 53.02%	" = .79

In this case, 48 developed garnet because of its much lower silica percentage. This verifies the experimental work of Ringwood and Green and explains the apparent anomaly of two coexisting metamorphic subfacies. The production of garnet is only useful as an indicator of metamorphic grade in saturated rocks.

The experimental results also enable an estimate to be made of the conditions of metamorphism. By good fortune this is made relatively easy, as 48 has a similar composition to the olivine tholeiite A used in the experiments and 194 is represented by the quartz tholeiite B, which has a slightly higher silica percent and higher iron-magnesium ratio (194 would then give garnet at a slightly higher pressure than quartz tholeiite B). (See Table 4) i.e. at 1,100°C. (see Fig. 15),

Qtz. Tholeiite B = 194, gives garnet at 14 Kb.
Ol. Tholeiite A = 48, gives garnet at 12Kb.

Since 48 has garnet and 194 has not, at 1,100°C the pressure corresponding to this mineralogical relationship would be between 12 and 14 Kb, i.e. 13 Kb. Using a P-T gradient from Green and Ringwood (Fig. 16) it is possible to find the P-T relations at which this could occur. Note that the rocks are intermediate pressure granulites close to the transition to high pressure granulites. Further limiting relations are the stability curve

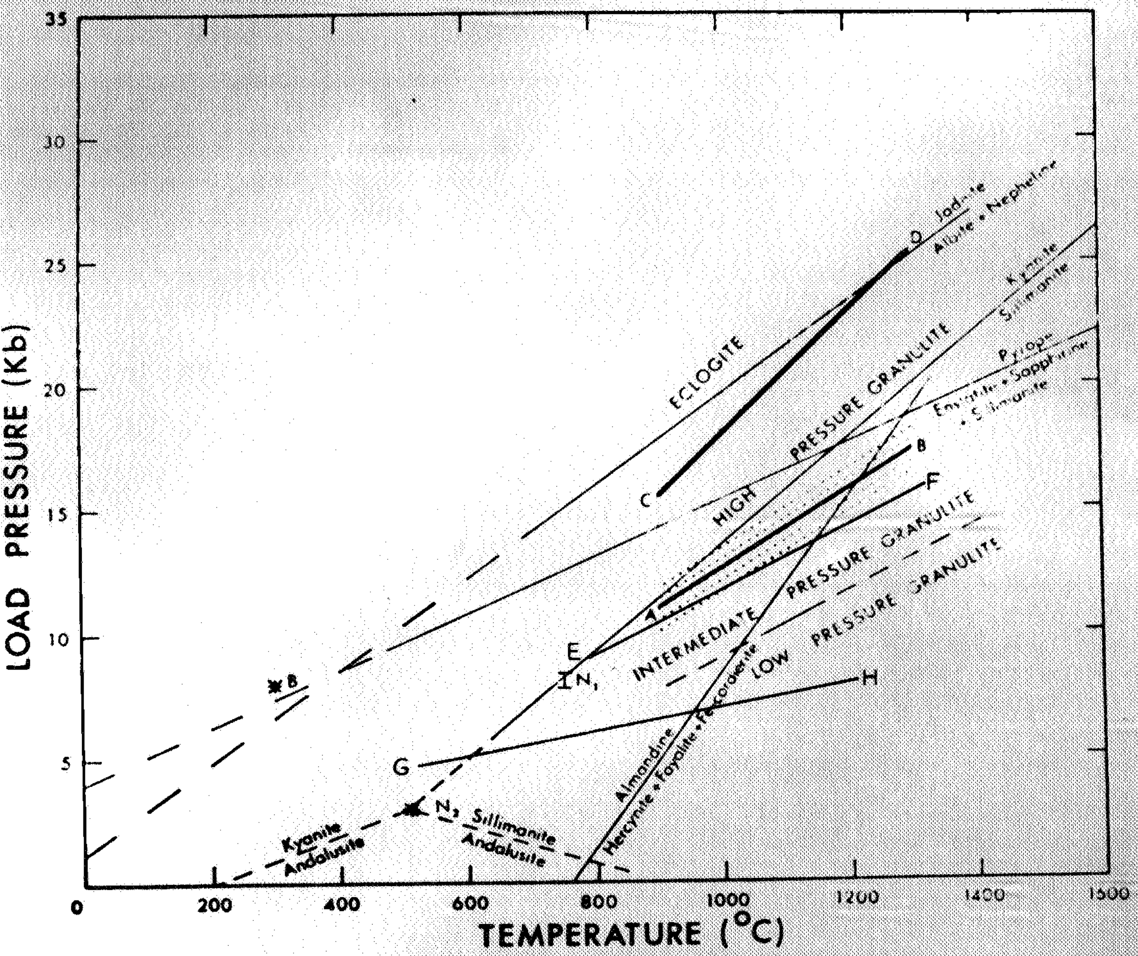


FIGURE 16 : P-T FIELDS FOR BASALTIC COMPOSITIONS AFTER GREEN AND RINGWOOD (1967).
AB = P-T GRADIENT OF GARNET APPEARANCE.
EF = TEIZI P-T GRADIENT
GH = P-T GRADIENT FOR : Ol + Plag (Low P.) ⇌ Opx + Cpx + Sp (High P.)

of garnet and the aluminosilicate polymorph boundary, as sillimanite is the only Al_2SiO_5 mineral found in the Mt. Davies area. The conditions of metamorphism of the Teizi rocks must lie on the gradient between 9 Kb, 800°C. and 13.5 Kb, 1,130°C. i.e. a depth range of 33-50 Kms. Since the Mohorovicic discontinuity probably occurs at around 44 Kms, it is possible to restrict this to 33-44 Kms.

A further useful P-T relation is derived from the spinel-orthopyroxene symplectite of the picrite, which results from the solid state reaction:

olivine + plagioclase $\rightleftharpoons$ orthopyroxene + clinopyroxene + spinel

A P-T gradient giving the conditions of reaction according to Kushiro and Yoder (1966) is plotted in Fig. 16. Since this was found for the simple system forsterite - plagioclase, it may be unreal and not applicable. Two explanations for the absence of garnet in the rock are (1) lower pressure of reaction as suggested by the P-T gradient and younger age of the rock or (2) composition unfavourable to garnet formation. Any P-T gradient can be crossed in two limiting ways (1) at constant pressure and (2) constant temperature - the picrite reaction, because of the rock's undeformed and unrecrystallised texture, probably resulted from cooling at constant pressure.

A general feature indicative of high pressure conditions is spinel exsolution in clinopyroxene of the picrite and some dykes.

CLASSIFICATION OF THE TEIZI METANORTHOSITE

Anorthosite classifications have been proposed by Buddington (1939) and Berrangé (1965), involving separation into two groups, massif and stratiform.

The Teizi Metanorthosite is a massif anorthosite according to Buddington, corresponding to type (2), "masses of small to very large areal extent without obviously strongly differentiated stratiform characters and with areal domical structure or structures in the roof of large bodies, such as the Adirondacks . . ." The somewhat more rigorous classification of Berrangé can be used as follows:

1) Environment: Massifs are confined to granulite facies terrains (if in amphibolite facies evidence for retrogression is usually found), stràtiform are not. This certainly applies to Teizi and it is likely that granulite facies, or at least high temperature-pressure anhydrous conditions, are necessary for massif formation.

2) Age: Massif anorthosites are restricted to the Precambrian. Teizi is definitely Precambrian as the unmetamorphosed Tollu Volcanics which overlie the basement granulite complex have been isotopically dated at 1,100 million years. This has no great significance as it naturally follows from (1). Stratiform anorthosites can have any age, but it is noticeable that all large developments are found in the Precambrian.

3) Form: Flat or tilted sheet and nappe-like forms are claimed to be typical of massif anorthosites. However,

anorthosites also have sheet-like form within basic intrusions and will appear similar if the intrusion is concordant. The Teizi Metanorthosite is a folded concordant sheet.

4) Internal Structure: Massifs are generally massive with little layering, which if present is parallel to kinematic foliation. Concordancy of gneissic structure of country rock and anorthosite foliation is characteristic. This is true of Teizi. However, major and minor layering is also reminiscent of the stratiform anorthosites in its persistence and repetition, even though the rock has a metamorphic texture, so that this feature is problematic.

5) Texture: Coarse grain size and ultrametamorphic textures such as bending and breaking of feldspar grains are common in massif anorthosites. However, these are not sound criteria as stratiform anorthosite-troctolite bodies may show them - certainly they occur at Teizi (pyroxenes up to ten inches long and cataclastic textures).

6) Mineralogical Composition: Commonly massif anorthosites show a gradation from anorthosite to younger mafic facies - norites and gabbros - which occur near the margins. Mafic facies occur at Teizi, but are of small volume and have sharp contacts with the anorthositic rocks on macro- and mesoscopic scales. Little variation is found in plagioclase composition (often antiperthitic), this being in the range An_{40}-An_{60}. The mafic minerals are orthopyroxenes with subordinate clinopyroxene, garnet and hornblende. The common accessory minerals of massifs are apatite

and ilmenite. A most remarkable feature of Teizi is the absence of apatite and most accessory minerals, except opaques and rare biotite and hornblende. The sequence of mineral compositions in stratiform anorthosites is governed by the principals of magmatic differentiation and often shows regular progressions.

7) <u>Associated Salic Rocks:</u> Massif anorthosites are often associated with younger pyroxene-perthite salic rocks of ultrametamorphic to igneous aspect. Their relationship to the anorthosites is controversial and has not been settled. These do not occur near Teizi, although possibly some of the charnockitic rocks of the Mt. Davies area might be considered as mangerites. The quartz-perthite granulite country rock is not in the author's opinion of this type because of its high quartz content and great extent.

Classification as a massif type is suggested for the Teizi Metanorthosite, conformity, metamorphic texture and feldspar composition being the strongest evidence. The prominent layering is identical to that found in many stratiform basic complexes and suggests at least some affinity with these. It is the first anorthosite of massif character described in Australia.

Study of recently described examples indicates that a sharp division between stratiform and massif anorthosites is unreal - they are end members of a continuous series. The Berrangé classification, as a very refined method of separating the end members, has revealed the large number of exceptions to a rigid classification - the Teizi Metanorthosite is one. That such a series exists provokes the question - Are the genetically related?

GENESIS

The principal hypotheses of origin proposed for anorthosites are:

(1) Magmatic: (stratiform or massif with various parent magmas and processes).

(2) Metasomatic: introduction of sodium and calcium.

(3) Assimilative: assimilation of pelitic rocks by basalt. i.e. magmatic.

(4) Metamorphic: metamorphic differentiation (under gravity?)

(5) Anatectic: anorthosite as a residuum after partial melting, or a plagioclase liquid as a result of partial melting.

Since the Teizi Metanorthosite has both massif and stratiform characters all the possibilities must be considered (n.b. (2)-(5) for massif only).

The theories of origin are simplified as follows: the assimilative origin involves only the production of the parent magma and is included under magmatic, and the only case where a metasomatic origin has been proposed, has a surrounding halo of decreasing feldspar content which is not present at Teizi - there is no positive evidence for this process and it is summarily dismissed.

The possibilities are then:

(1) Metamorphic

(2) Anatectic

The following is a brief discussion of these three possibilites.

Metamorphic Origin

The concordant country rock and metanorthosite foliation and layering is suggestive of development of the foliation and layering during a previous deformation and may imply that anorthosite formation was a metamorphic process. Firstly, no evidence for this previous deformation has been found and although it is highly likely that it did take place, the anorthosite need not have been in situ then. An alternative and plausible explanation of foliation orientation can be given.

It is difficult to invoke isochemical metamorphism, assuming the rocks to be metamorphosed sediments, because of the rarity, if not non-existence of sediments of the correct composition. Metamorphic differentiation is difficult to disprove, but is not supported by the extreme geochemical contrast between the metanorthosite and the quartz-perthite country rock - it has no positive evidence in its favour apart from the partly gradational contact and occasional pyroxene granulite layers in the country rock.

The metamorphic model can be rejected conclusively because of the absence of rubidium in the rocks. Crustal rocks show marked rubidium contents and consequent low potassium-rubidium ratios, while the metanorthosite contains no rubidium within the detection limit of the X-ray fluorescence spectrograph. Derivation from a source region of low rubidium is implied, this being the mantle. Also difficult to explain is the perfection of interlayering of metanorthosite and pyroxene granulite (i.e. the layered units), a feature not observed in any other granulites during the author's sojourn in the field.

Anatectic Origin

Two distinct proposals of anatectic origin have been made:

1. Anatexis of lower crustal material of intermediate composition leading to a feldspathic residuum and acidic liquor.
2. Melting of amphibolite under hydrous conditions producing an anorthositic liquid and hornblendic residuum.

The first can be rejected on similar grounds to those above - high rubidium content would be expected in such a residuum and it is difficult to see how an anatectic process would develop the layering found. Conformity of foliation and layering is however simply explained by this process.

The second model is interesting in that the low rubidium content would be accounted for (amphibolites of basaltic parentage would have low rubidium), but falls down badly in a general way through its inability to explain the granulite facies association of metanorthosites, as the conditions under which this melting can take place are not severe and could be expected in much lower grades of metamorphism.

The remaining hypothesis is that of magmatic origin, which will be considered in greater detail because of its ability to account for the features of the metanorthosite in a simple and more complete manner than any other.

Magmatic Origin

The following features suggest a magmatic origin:

1. An anorthosite period of igneous activity as evidenced by the anorthositic dykes.
2. The well-developed interlayering of metanorthosite and pyroxene-plagioclase granulite in the layered units, which is identical to that found in many layered intrusions.
3. The low rubidium content which is indicative of a mantle source region.
4. The composition of the rocks which is identical to that found in definite anorthositic intrusions.
5. The equilibrium potassium-sodium relationship of the plagioclases.
6. The presence of pegmatites.
7. The association with the Giles Complex with which it has many similarities (this will be discussed in more detail later).

Possible objections to the magmatic hypothesis are:

1. The An_{50} plagioclase composition. However anorthositic layered intrusions (e.g. Freetown An_{56-64} and Michikamau

An_{52-62}) can have this composition and plagioclase has been found experimentally to become more albitic with increased pressure. Experimental investigations of basaltic compositions have unfortunately not included plagioclase determination.

2. The absence of marked magmatic differentiation. This is however limited to the above examples.
3. It might be suggested that igneous layering would not survive granulite facies metamorphism, but metamorphosed stratiform anorthosites in Greenland (identified by the presence of chromite layers) show perfect preservation, even on the scale of graded layering (Windley, 1967). Interestingly, until the discovery of the chromite layers these were classified as massif anorthosites.

The Nature of the Parent Magma

A wide variety of magmas have been suggested as playing an important part in anorthosite genesis.

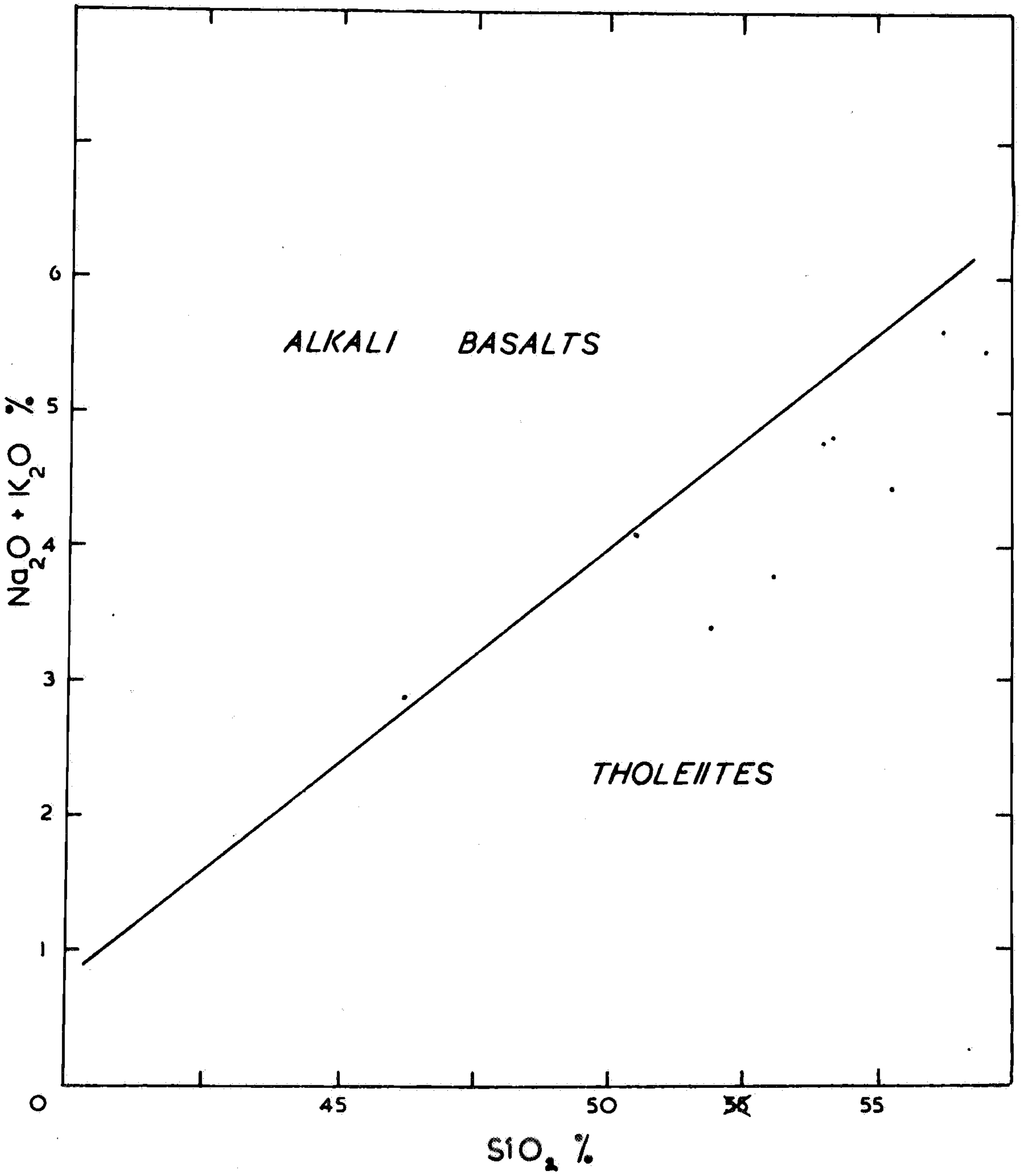
1) Basaltic - applied by many to stratiform anorthosites, e.g. Wadsworth (1963), Emslie (1965) and to massif anorthosites e.g. Bowen (1917).

2) Gabbroic Anorthosite - Buddington (1961).

3) Diorite or Quartz Diorite - Philpotts (1966), Green (unpub.)

The most popular at the moment are the basalt for stratiform anorthosites and for the massifs, the intermediate composition magma, a plutonic member of the calc-alkali series which has a

FIGURE 17 : TOTAL ALKALIS VERSUS SILICA



large field of initial plagioclase crystallisation. As regards the Teizi parent magma there can be little more than speculation. The calc-alkali hypothesis is supported by the constant iron-magnesium ratio, but as can be seen in fig. 10 this is also a feature of the early crystallisation of the Mt. Davies Intrusion. It is tentatively suggested that because of the metanorthosite's affinities with the Giles Complex the ultimate parent was of basaltic (tholeiitic) composition and that differentiation with constant FeO/MgO is characteristic of anorthosite crystallisation, as that part of Mt. Davies in which this is so, also contains anorthosite. Tholeiitic character is shown in fig. 17, a plot of total alkalis versus silica for the metanorthosite rocks. Basaltic parentage must be proposed for the Bell Rock, Blackstone and Cavenagh Intrusions of the Giles Complex whose lithologies are olivine anorthosite and troctolite (An_{60-65}) and has been suggested for the Michikamau Anorthositic Intrusion of Labrador, which has a basaltic chill zone.

Relation to the Giles Complex

Because of the proximity of the Teizi Metanorthosite and the Giles Complex an obvious postulate is to relate the metanorthosite to this phase of basic intrusion.

The following common features can be used to support this hypothesis:

1) Geographic proximity.
2) Identical igneous layering.
3) Conformity of layering and foliation of intrusion and country

rock (Kalka is the Giles Complex example - A.D.T. Goode, pers. comm.)

4) $FeO/MgO = k$ differentiation.

5) Tholeiitic character.

6) Rutile exsolution in orthopyroxene.

7) Absence of accessory minerals, particularly apatite, which is normally common in basic and metanorthositic masses.

8) Absence of rubidium.

Objections may take the form:

(1) Teizi plagioclase composition (An_{50-60}) is different to that of the Giles Complex. Exceptions such as Gosse Pile plagioclase (often An_{50} - A.C. Moore, pers. comm.) and the An_{60-65} range of Bell Rock etc., suggest that this is not important.

(2) The metanorthosite has been metamorphosed whereas the Giles Complex has not. However, the dykes of the metanorthosite area, ("Giles Dykes" - a minor phase of the Giles Complex - A.D.T. Goode, pers. comm.) have also been metamorphosed - conditions for metamorphism may have been more suitable in this region. It is not necessary to propose that this is a result of the action of a much older metamorphic period on the anorthosite.

None of the above arguments are conclusive. Since there is no positive objection to the postulate and in view of the similarities a tentative relation to the Giles Complex is proposed.

It is interesting to note the common association of massif anorthosites with intrusive basic provinces; e.g. Canada (Keweenawan basic intrusives and the Quebec anorthosites), Angola, Norway, Madagascar, India and now Australia - see Berrangé (1965). This of course does not necessarily mean close relationship.

SEQUENCE OF EVENTS

The early history of the granulite country rock is obscure, this thesis first noting a period when layering was relatively unfolded and intruded by a magma which crystallised predominantly plagioclase forming a layered anorthosite sill. This was later folded into a shallow-plunging antiform, it being assumed that the body is not overturned.

Interpretation of the composition changes as a differentiation sequence is not easy (a common feature of anorthosites). Most striking is the marked geochemical change which occurs at the inner layered unit. Plagioclase composition, which varies smoothly, reaches a maximum there, as the modal plagioclase percent is a minimum. Strontium in plagioclase is a minimum, but reaches its maximum in the outer blue metanorthosite, suggesting magma enrichment in strontium due to little being incorporated in the more calcic plagioclase of the inner layered unit. The reason for the geochemical break and increased crystallisation of mafic minerals is not known. Later metamorphism has little affected the phases of the metanorthosite rocks as rutile exsolution, which is destroyed on recrystallisation, is still common in the orthopyroxene.

Folding followed intrusion producing the antiformal structure and foliation. It is proposed that the foliation parallel to folded layering need not require an initially planar foliation produced by an earlier deformation. The mechanical properties of almost pure plagioclase rocks are suggested to be such as to produce stresses during folding that cause elongation of pyroxene clots and phenocrysts parallel to the layering (a type of bedding plane slip?). Phenocrysts with associated granulated tails in the foliation plane (see sketch - fig. 18), are evidence for this process. As in addition the intrusion is conformable, metanorthosite layering and foliation will be conformable with that in the country rock. Since such relations are found in the definitely intrusive Giles Complex, such a process must have occurred.

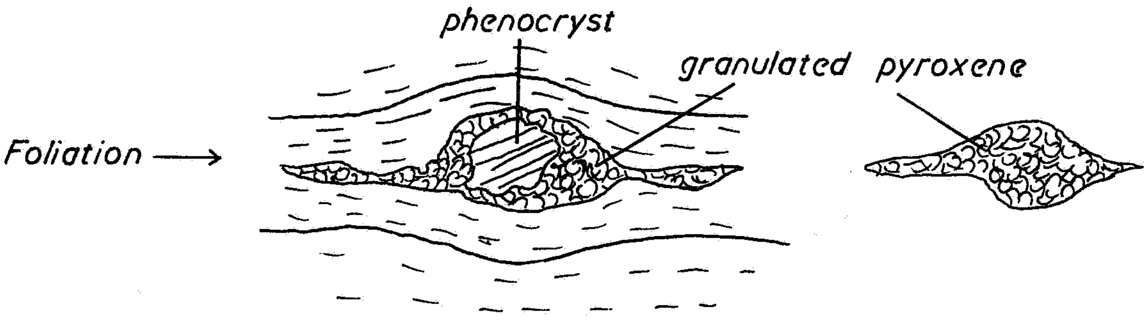


FIGURE 18 : DEFORMED PHENOCRYSTS

Post-dating the folding was the intrusion of the "metamorphosed" dykes along fault planes related in part to the folding. Temperature contrast between wall rock and dyke was sufficient to allow rapid cooling and preservation of a quite high structural state in the plagioclase.

Since the dykes and metanorthosite have the same metamorphic grade and show the same metamorphic reactions in progress, it is likely that they have been subjected to only one period of granulite facies metamorphism. There is no indication of the time span of metamorphism and its relation to the folding, but the obvious conclusion is that they are in part related, even though the metamorphosed dykes post-date folding. It is theoretically possible to form garnet in basic dykes by cooling at constant pressure (see fig. 16), but because of kinetic difficulties reaction will only proceed under favourable conditions of high temperature and pressure and deformation, which will probably be consistent with the granulite facies. Metamorphism may have begun during folding and later dykes crystallised under granulite facies conditions.

Some time after metamorphism, intrusion of the undeformed picrite plug occurred. This body is typical of late stage Giles Complex intrusions, so that the main Giles intrusive activity probably took place before this.

The foliated dykes are difficult to place in this relative scheme, but must post-date the folding and presumably the metamorphism, since original plagioclase laths are found and the only deformation is shearing with "pseudotachylite" formation (recognised as a relatively young event in other areas).

The general sequence is:

<u>Time</u> →

Granulite Formation - Anorthosite Intrusion - Folding - "Metamorphosed" Dyke Intrusion - Metamorphism - Picrite Intrusion - (?) Foliated Dyke Intrusion.

A.D.T. Goode (pers. comm.) has proposed the following sequence for the Giles Complex:

Anorthosite Intrusion - Folding and Granulite Metamorphism - Foliated Dyke Intrusion - Giles Complex, Giles Dyke Intrusion, Deformation and Recrystallisation - Olivine-rich Plugs (i.e. picrite) - Other Dykes (not found in the Teizi area) - Brittle Mylonites.

These sequences can be matched if the Giles Complex was intruded during a single folding episode corresponding to that in the Teizi area. The only disagreement concerns the foliated dykes, which could well have been intruded post-Giles Complex because they are unfolded. This provides a new interpretation of the Giles Complex, the sequence of events being as in the first case above, with Giles intrusion in the same time span as anorthosite intrusion, the anorthosite being more severely metamorphosed because of earlier intrusion in the height of metamorphism or different physical conditions of intrusion.

CONCLUSIONS

The Teizi Metanorthosite is a metamorphosed, conformable stratiform anorthosite. Igneous characters include anorthositic dykes, igneous layering, low rubidium content and plagioclase geochemistry. Metamorphism of the area to intermediate pressure granulite facies post-dated intrusion and affected dykes related to the Giles Complex which crosscut the metanorthosite. It was responsible for the development of features found in massif anorthosites. Experimental work related to the metamorphism of basic rocks enables an estimate of the physical conditions of metamorphism to be made.

Since a series of anorthosite types from stratiform to massif is found in nature, it is suggested that these may have a common origin. In particular it is proposed that formation of massif anorthosites can be accomplished by granulite facies metamorphism of stratiform anorthosites.

FUTURE WORK

Detailed examination of country rock structure and petrology, including the other anorthositic bodies, which appear structureless, is necessary to relate the Teizi Metanorthosite to the Giles Complex. Following this a geochronologic and isotope geochemical study would be of great value.

The dykes of the area cry out for investigation. Their geochemistry, in particular metamorphic reactions and their relation to experimental work, and petrogenesis are of prime importance in understanding the Giles Complex.

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APPENDIX I

Sample collection and preparation.

Approximately 1000 grms. of rock was collected at a particular location by spalling of fragments with a six pound hammer. Care was taken to obtain relatively unweathered material and this was generally achieved. The sample was then numbered and stored in polythene bags.

After thin section examination, 500 grms. of rock were broken into small fragments and the pieces then reduced to minus 44 mesh by manual crushing with a steel pounder. The sample was then split, half being retained for feldspar separation and a quarter manually crushed to minus 120 mesh for whole rock analysis. (Manual crushing was recommended in order to reduce contamination in the case of trace element analysis).

Separation of plagioclase was achieved from a washed -70+120 mesh fraction using a Frantz Isodynamic Separator. Currents up to 1.3 amps and several runs were necessary to obtain a clean sample which was further checked by microscopic examination.

Feldspar Analysis

The separated fraction was finely ground, dried at 110°C. and weighed into a platinum crucible. Digestion was carried out using constant volumes of HF and H_2SO_4, the solution being made up to volume (100 mls) after evaporating off the HF.

Sodium and potassium were determined by flame photometry using an Evans Electroselenium flame photometer. Standard sodium solutions prepared from sodium oxalate and stock potassium standards were used. Blank solutions were very low and excellent precision within the error of experimental measurement was found.

Calcium analysis was by EDTA titration. The reagents used were: unknown solution (10 mls), triethanolamine (5 mls - complexes iron and aluminium), NaOH (3 mls, 10%), water (5 mls) and 12 drops of .1% acid alizarin black in water. Photometric titration using acid alizarin black as an indicator enabled graphical solution for the end point. Comparison with the titration of a 5 ppm CaO standard gave the unknown. All titrations were done in duplicate.

The feldspar analyses were checked by analysing "Crystal Bay plagioclase" the laboratory standard. The following comparison of values was obtained:

<u>Crystal Bay Plagioclase Analyses</u>

	AMDL	J.D. Kleeman (1965)	C.M. Gray (1967)
Na_2O%	3.15	3.22	3.12
K_2O%	.17	.18	.19
CaO%	14.3	14.3	14.3 { 14.29 14.27

<u>Diffractometry</u>

Powders ground mechanically for half an hour were used for smear mounts on quartz plates for X-ray diffraction. Four diffractometer oscillations were made for Γ and B, the smear being remade and another four oscillations made so that an equal number of ascending and descending traverses were made in order to reduce instrumental errors. Peak spacing was measured at two thirds peak height, and the parameters calculated.

WHOLE ROCK ANALYSIS

Na, K, Mg, P and Fe^{II} were determined by wet chemistry, Mn, Ca, Ti, Fe (total) Al, Si and K by X-ray fluorescence spectrography.

Wet Chemistry

One hundred milligrams of sample was weighed accurately and digested using HF (8 mls) and H_2SO_4 (.5 mls). After heating overnight, $HClO_4$ (1 ml) was added, the solution evaporated nearly to dryness, extra $HClO_4$ (1 ml) added and the crucible half filled with water. When dissolved, the solution was made up to 250 mls.

Sodium and potassium were determined by flame photometry as described for the feldspars.

Magnesium analysis was by atomic absorption spectroscopy. The instrument used was a Techtron atomic absorption spectrograph with a nitrous oxide-acetylene flame. Comparison of absorbance versus ppm MgO for a series of synthetic standards allowed determination.

Ferrous iron was determined using a modified Washington method involving titration with standard potassium permanganate. Digestion of a weighed sample was by adding a near boiling mixture of H_2SO_4 and HF to the moist powdered rock in a platinum crucible, rapidly sealing with a lid and heating for ten minutes. The crucible was then plunged into a beaker containing H_2O (300 mls), H_2SO_4 and H_3BO_3 (to remove HF) and titrated rapidly with potassium permanganate (.1N). Quite good precision was obtained, relative variation of duplicates often being less than 1.5%.

Phosphorus was determined by the method of Riley, i.e. spectrophotometric comparison of the molybdenum blue complex of phosphorus with a prepared standard using a Unicam SP 600 spectrophotometer.

X-ray Fluorescence Spectroscopy.

Major element analysis by means of X-ray fluorescence was carried out in the standard practice of the department. Borate buttons were prepared using the following weights of material - borate mix (1.875g.), sodium nitrate (0.25g.) and rock sample (.35g.). Using the standard diabase W1 as a drift standard, determination of the time for a fixed number of counts was carried out on all the unknowns and CaO and quartz blanks. The counting data was modified to allow for drift and deadtime (3.0×10^{-6} secs) and converted to counts per second. Using the measurements on W1 crude counts per second per percent oxide values were calculated allowing for interelement effects by means of the Norrish factors. These divided into the corrected counts per second for the unknowns gave crude analyses which were refined for matrix effects by means of the Silian computer program.

Trace Element Analysis by X-ray Fluorescence

Feldspar and whole rock samples were prepared in the form of three grams of unknown in a boracic acid-backed pressed pellet (applied pressure = 3 tons). Rubidium and strontium were the elements analysed, counting being on the peak and background (both sides of the peak) with W1 as the reference standard. Time for fixed counts was corrected for drift, deadtime and background. Element concentrations were found by comparison with W1, with allowance for assumed or calculated mass absorption coefficients of unknown. A mass absorption coefficient of 8.8 for strontium K radiation was used for the plagioclases (measured for a very similar An_{51} plagioclase by A.C. Moore). Calculated mass absorption coefficients. were compiled from Philips tables of mass absorption coefficients.

APPENDIX II PETROLOGIC DESCRIPTIONS

A298-142: Core gabbroic metanorthosite

Hand Specimen: A medium-grained, even-textured rock with no directional characters. Black pyroxene (1.5mm, 15%) and grey interlocking plagioclase (2mm, 85%) are the prominent minerals.

Thin Section: Assemblage : orthopyroxene - plagioclase.

Plagioclase: (85%) Irregularly shaped grains (up to 5mm) with serrated edges. Antiperthitic with potash feldspar blebs developed along twin lamellae boundaries or oriented in a similar fashion in apparently untwinned grains.

Orthopyroxene: (15%) Irregular grains (up to 5mm) with occasional simple twinning. Pleochroic pink to green. Much included material: (1) clinopyroxene as large (.4x.02mm) irregular, elongate grains or fine well-oriented lamellae continuous with opaque material - more intense near a twin plane (2) rust coloured, translucent plates (3) rutile exsolution as needles of several orientations.

Accessories: Clinopyroxene - small grains in contact with orthopyroxene.

Texture: A cataclastic texture with large intermeshed irregularly shaped plagioclase crystals with some smaller (.3mm) interstitial grains and scattered interstitial pyroxene.

A298-196: Core massive metanorthosite

Hand Specimen: A fine-grained homogeneous plagioclase rock of indistinct texture. Colour varies from white to pale grey.

When wet, oriented augen-shaped grains can be seen.

Thin Section: Assemblage : plagioclase.

Plagioclase: (100%) Augen-shaped grains (2.5mm) with long axes of similar orientation between which are granulate patches. Poorly developed twin lamellae also parallel this direction $2V_x = 85 - 90^o$. The feldspar contains many inclusions, (1) opaque euhedra in discontinuous trains with an almost rhombohedral pattern. (2) Unidentified, colourless inclusions in wavy trains - probably calcite. Grain boundary alteration is strongly developed with formation of small calcite grains and an unidentified fibrous, tufty mineral, which is continuous around the plagioclase - the calcite (?) inclusions in the plagioclase are probably related to this.

Accessories: Rare, severely-altered clinopyroxene.

Texture: A markedly cataclastic texture with oriented augen-shaped grains, granulation and bending of twin lamellae.

A298-110: Core blue metanorthosite.

Hand Specimen: A grey, medium to coarse-grained, dense rock made of black pyroxene (1mm, 5%) in small evenly scattered clumps and grey, interlocking, irregularly-shaped plagioclase crystals (4mm, 95%).

Thin Section: Assemblage : plagioclase - orthopyroxene.

Plagioclase: (90%) Very irregular grains (3mm) with serrated, interlocking edges. Poorly defined multiple twins have spindle -like terminations - lamellae are sometimes bent. The mineral is antiperthitic with included potash feldspar of square to elongate wedge shape, aligned along twin lamellae and fractures. Opaque inclusions are small euhedra aligned similarly to the potash feldspar, $2V_z \sim 85^\circ$.

Orthopyroxene: (10%) Irregularly shaped grains (10mm.) Pleochroic - X = pink, Y = pale green, Z = green. $2V_x \sim 80^\circ$, i.e. a bronzite. It contains exsolved rutile as fine oriented needles and unidentified, rust-coloured oriented plates. Very thin rims of an unidentified green alteration mineral (amphibole or chlorite ?) occur in places.

Accessories: Clinopyroxene-small grains between or marginal to orthopyroxene. Non-pleochroic, $2V_z = 60-65^\circ$. (1%).
Biotite-blades associated with opaques. Pleochroic-yellow-brown to deep red-brown.
Hornblende-small grains marginal to orthopyroxene.
Opaques-haematite-ilmenite exsolution intergrowth.

Texture: Typical metanorthosite texture - large interlocking plagioclase grains with some interstitial granulation. Pyroxene occurs as irregularly distributed grains of varying size, i.e. a cataclastic texture.

A298-119B: Inner Layered Unit.

Hand Specimen: A medium-grained rock containing grey to white plagioclase (1-2mm, 20%), black pyroxene (1mm, 25%) and pink garnet (1mm, 20%). A crude layering is defined by narrow (one grain width), discontinuous mafic layered separated by plagioclase - rich bands (2mm wide).

Thin Section: Assemblage : plagioclase - garnet - clinopyroxene.

<u>Plagioclase</u>: (55%) Irregular grains (2.5 - .3mm) which are not antiperthitic and contain few opaque inclusions. Spindle twinning is prevalent. $2V_z = 80^\circ$.

<u>Garnet</u>: (25%) Subrounded to euhedral grains (1 mm) - very pale pink colour and always isotropic. Often contains small, oriented, opaque and transparent needle-shaped inclusions. Occasional grains have rounded spinel, opaque or rare plagioclase and clinopyroxene in their centres.

<u>Clinopyroxene</u>: (20%) Irregular, non-pleochroic, green grains (.45 mm), with central opaque inclusions. Always associated with garnet. $2V_z = 55\text{-}60^\circ$ (strong dispersion).

<u>Accessories</u>:

Spinel-isotropic green globules in the centres of garnet.

Opaques-haematite in ilmenite exsolution intergrowth.

Amphibole, biotite and rare chlorite interstitial to some garnets.

The chlorite (pleochroic colourless to blue), may be due to breakdown of biotite to opaque and chlorite.

Texture: A granoblastic texture with crude mineral layering, plagioclase and plagioclase-clinopyroxene-garnet.

<u>A298-119D</u>: <u>Inner Layered Unit</u>.

Hand Specimen: A very even-grained rock of medium (1mm) grain size with no directional characters in hand specimen (selected to be homogeneous). Black pyroxene (1mm, 40%) in white plagioclase (1.5mm, 60%) are the minerals, giving the rock a spotted appearance.

Thin Section: Assemblage : plagioclase - clinopyroxene - orthopyroxene - hornblende.

Plagioclase: (55%) Irregular grains (1.5mm) with boundaries showing some tendency to triple points. Not antiperthitic with spindle-shaped twin lamellae and many opaque inclusions. $2V_z \sim 85^{\circ}$.

Clinopyroxene: (35%) Non-pleochroic, green irregular grains, Much included material (1) large, reddish oriented rectangles (2) well-oriented opaque needles in the centre of grains - mainly haematite with thin needles of exsolved ilmenite. Similar material occurs at grain boundaries (3) plagioclase oriented similarly to (2), (4) oriented transparent material - probably orthopyroxene.

Orthopyroxene: (10%) Pleochroic (pink to green) irregular to subhedral (.5-1.0mm) grains. Rutile exsolution is present, but is not as well-developed as in the other rocks. $2V_x \sim 70^{\circ}$.

Hornblende: (2%) Irregular grains developed laterally on ortho- and clinopyroxene. Amphibole cleavage noted. Pleochroic - pale yellow to green to brown-green.

Accessories: Biotite-small developments on the margins of ortho- and clinopyroxene, often with associated opaques. Opaques-exsolution intergrowths of haematite and ilmenite - spindle-shaped lamellae in two directions.

Texture: Crudely granoblastic, with some triple point grain intersections and even distribution of the minerals present.

A298-120: Outer blue metanorthosite.

Hand Specimen: A medium to coarse-grained, blue-grey rock of grey to white interlocking plagioclase (3-4mm, 95%) and black pyroxene (1mm, 5%) which is randomly distributed. This specimen contains slightly more pyroxene than is typical of this unit, the rock commonly having only accessory pyroxene.

Thin Section: Assemblage : plagioclase - orthopyroxene.

Plagioclase: (85%) Large irregular grains (5mm) with interlocking serrated edges. Some large grains are devoid of twinning. Inclusions - antiperthite not as marked as in other specimens, with potash feldspar aligned in ribbon-like clusters also contains opaques euhedra. $2V_z \sim 85^\circ$.

Orthopyroxene: (15%) Irregular grains, pleochroic pink to green. Included material: (1) exsolved rutile, (2) transparent, anisotropic lamellae - clinopyroxene (?), (3) rust-coloured material. Narrow, rim alteration to a blue-green mineral on some grains.

Accessories: Clinopyroxene.

Texture: As in 110.

A298-126: Outer Layered Unit.

Hand Specimen: A medium-grained, even-textured rock consisting of black pyroxene (1mm, 40%) and white plagioclase (60%, 1.5mm).

Thin Section: Assemblage : plagioclase - orthopyroxene.

Plagioclase: (70%) Irregularly shaped grains (1mm). 2V=90°. Markedly antiperthitic, but without included opaque euhedra.

Orthopyroxene: (30%) Rounded to subrounded grains (.5mm). Pleochroic: X = pink, Y = pale green, Z = green. Exsolution: rutile and rare transparent mineral exsolution in the same orientation.

Texture: Crudely granoblastic, with even distribution of phases and the development of "triple point" grain boundaries.

A298-194: Metamorphosed Dyke.

Hand Specimen: A dense, black porphyritic rock with black, subhedral pyroxene phenocrysts in a medium to fine grained groundmass of black pyroxene (60%) and white plagioclase (40%).

Thin Section: Assemblage : plagioclase - orthopyroxene - clinopyroxene.

Plagioclase: (50%) Angular, equidimensional grains (.4mm) with 120° grain boundary junctions. Contains occasional small, high relief, subhedral inclusions - spinel, apatite? Poorly developed spindle twins.

Orthopyroxene: (5% as phenocrysts, 20% granular) Phenocrysts are irregular in shape and in the process of granulation or recrystallisation. (2.5mm). Some contain zoned clinopyroxene exsolution, as well as rutile exsolution. Moderate to weakly pleochroic. Groundmass opx (.3mm).

Clinopyroxene: (25%) Non-pleochroic grains in "groundmass" Form as for opx.

Accessories:

Biotite-pleochroic from yellow to mahogany.

Opaques-ilmenite with spindle-shaped blebs of exsolved haematite. Rare pyrite and chalcopyrite.

Texture: A granoblastic texture, with relic igneous orthopyroxene phenocrysts in the process of recrystallisation.

A298-48: Garnet-bearing Metamorphosed Dyke.

Hand Specimen: A medium to fine-grained, dense, grey-coloured, rock with black indistinct pyroxene grains, small, white plagioclase grains and associated garnet.

Thin Section: Assemblage: plagioclase - clinopyroxene - garnet.

Plagioclase: (40%) Little-twinned, angular grains with much opaque and transparent included material. Relic simple twins eroded at the edges by garnet and clinopyroxene.

Garnet: (30%) Euhedral to granular pale-pink grains. Occurs in clumps with clinopyroxene and rare relic orthopyroxenes.

Clinopyroxene: (30%) Irregular grains associated with garnet.

Accessories:

Orthopyroxene - associated with garnet.

Biotite - occurs in mafic clumps. Pleochroic-pale-orange to deep red.

Ilmenite - contains some haematite needles.

Texture: Crudely granoblastic with mafic clumps of garnet and clinopyroxene. Textural and chemical equilibrium have been reached in this rock following garnet producing reactions.

A298-320: Picrite (from plug) (brief thin section description)

Thin Section: Assemblage: olivine - spinel - clinopyroxene - orthopyroxene - plagioclase - hornblende.

Olivine: Euhedral to rounded grains often poikitically enclosed by pyroxene. 2V = 90°. Where contact is made with interstitial plagioclase, reaction rims occur. Small trains of oriented globules of a transparent mineral may have resulted from exsolution.

Spinel: There are five distinct spinel associations.

1) perfect cubes mainly enclosed in olivine, rarely other minerals.
2) exsolved blebs in clinopyroxene.
3) small tubules in an orthopyroxene - spinel symplectite.
4) small tubules in some hornblende.
5) many small euhedra enclosed in plagioclase.

Clinopyroxene: Non-pleochroic, large grains poikilitically enclosing olivine. Contains much exsolved spinel except in a few regions remote from other grains where exsolution is less intense or absent.

Orthopyroxene: Rare as individaul grains, often found as thin reaction rims on olivine where there are olivine-plagioclase contacts. Two forms are noted (1) a thin rim of orthopyroxene (2) an outer symplectite of tubular orthopyroxene and green spinel.

Plagioclase: Irregular grains interstitial to other phases. Little twinning. Characterised by the extreme development of an included, colourless, euhedral mineral of "monoclinic" shape. This was identified as spinel by Professor A.F. Wilson and by analogy with other rocks in the area. The inclusions are oriented in similar fashion and varying density in apparent relation to twin lamellae directions.

Hornblende: Large, interstitial, irregular grains, or as small developments on clinopyroxene. Pleochroic: pale yellow to tan. Contains tubular green spinel. Opaques and biotite are commonly associated.

Texture: A typically igneous texture, indicating initial crystallisation of euhedral olivine and spinel, followed by enclosing clinopyroxene and finally interstitial plagioclase. Solid state reaction has produced a spinel-orthopyroxene ± clinopyroxene symplectite where olivine crystals abut interstitial plagioclase.

GEOLOGICAL MAP

OF THE

TEIZI METANORTHOSITE