PETROLOGY OF THE WHITESTONE ANORTHOSITE

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The conclusions of this thesis rest on comprehensive geological, chemical and petrographical analyses of both the Whitestone anorthosite and the contiguous rocks.

The anorthosite is believed to have been intruded as a magma of anorthositic composition just after the acme of the last regional metamorphism. Various textural and mineralogical features, ostensibly metamorphic, are interpreted as being due to an extravagantly long magmatic end-game.

ABSTRACT

A review of current petrogenetic theory indicates the most contentious issue to be the relation of massif anorthosites to their surrounding rocks; in many cases these latter have been interpreted as orthogneisses.

In the Whitestone area the anorthosite is shown to have developed both a metamorphic and a metasomatic aureole in the adjacent rocks which, in this case, are a heterogeneous paragneiss suite. These paragneisses were already of upper amphibolite grade and the contact effects have been superimposed on them: there is no evidence of any regional metamorphism since the development of this aureole. The rare assemblage, clinopyroxene-garnet±orthopyroxene, which is developed in the aureole, is a result of the unusually low Mg/Fe ratio of these rocks due to the iron metasomatism imposed by the anorthosite. A prima facie case is made that such an aureole is present around other anorthosites.

There is abundant evidence of the development and activity of an iron-titanium-volatile-rich fluid phase which was responsible for the metasomatic aureole and the minor oxide showings -- both concentrated at the top of the body. Novel is the proposal that this fluid phase together with a protracted cooling interval and minor accommodating movements (perhaps occasioned by the arrival of new magma) are responsible for the many ostensibly metamorphic aspects of the anorthosite: viz., development of scapolite, hornblende, orthopyroxene (and the green feldspar

facies), garnet and epidote and also the recrystallisation of the primary minerals. It is important to emphasise that these "autometamorphic" features are independent of, and post-date, the regional metamorphism.

The primary plagioclase and clinopyroxene show little or no significant compositional variation despite evidence of crystal accumulation. The pyroxenes of the anorthosite are chemically distinguished from those of tholeiitic and alkalic intrusives especially by a high value for both octahedral and tetrahedral aluminum. This results from the highly aluminous state of the anorthositic magma. It is tentatively proposed that this is a derivative magma originating from a "basaltic-type" magma by complete separation of early forming mafic minerals.

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CHAPTER 1

ANORTHOSITES AND ANORTHOSITES AND....

AN INTRODUCTION

1a. Preamble

Contrasting with the wholly inductive approach of early petrologists the modern worker has witnessed the birth and confirmation of many sturdy and promising petrological theories from the crucibles of experimental geochemists. Often the seed for these experimentally based theories has been germinated by controversy over the interpretation of careful field work. Moreover, this field work, by highlighting the crux of the problem, often suggested appropriate simplifications necessary for the laboratory study of complex natural systems.

Underlining the complementary nature of the two approaches, natural and experimental, H.S. Yoder Jr. suggested at a recent symposium on the genesis of anorthosites several different origins for anorthosites which were all compatible with recent experimental work, but none of which could be favoured on its own merits, possibly because none of the basic experimental work was carried out with the genesis of anorthosites specifically in mind. The present study was undertaken partly to re-examine the field data on anorthosites in the light of this modern work, and also in the hope that this study would suggest convenient, confirmatory experimental projects.

1b. Anorthosites and their Genesis

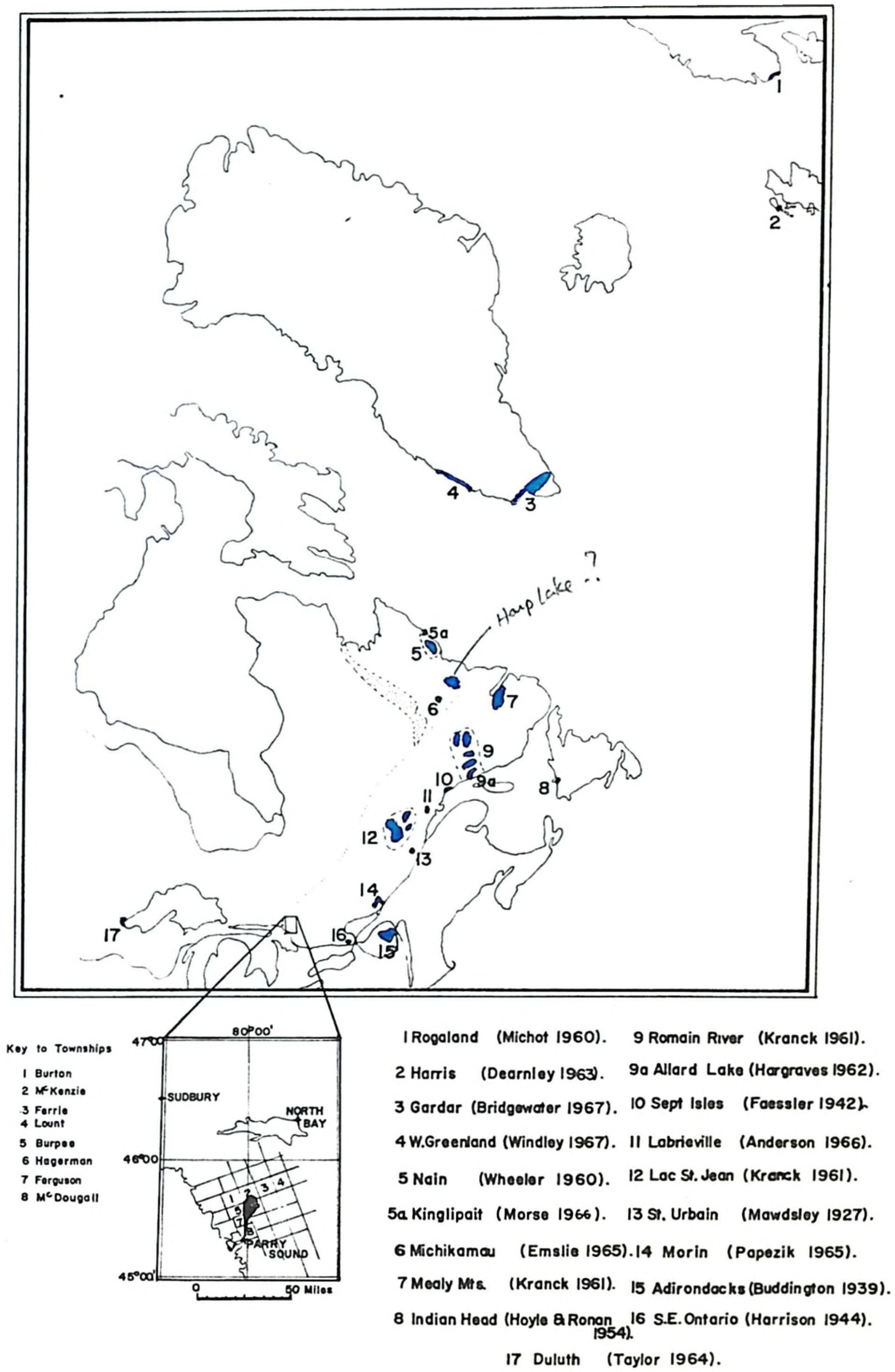
1b(i) Introduction

A remarkable fact concerning these enigmatic bodies of rock passing under the name anorthosite is that they are all Pre-Cambrian in age. This, of course, has been noted by many authors and several theories explaining this feature will be discussed later, but at this point it is noted that a natural corollary of this fact is that most of the anorthosites reported in the North American and West European literature are found in the Canadian Shield. Other occurrences are found in similar or identical shields (depending on your views on the diaspora of the continents) in Greenland, Scotland and Norway. Fig. 1-1 locates and gives the most recent references to all(?) anorthosites in this region. Other North American anorthosites (also Pre-Cambrian) are known and reference will be made to these as appropriate.

Romey (1968) gives references to various anorthosites in the Siberian Shield and many anorthosites are known from the Indian Shield (De 1966, Subramaniam 1956 a & b) but due in large part to obvious literature difficulties less attention will be paid to these in this thesis. However, it is hoped that the wide variety of anorthosites found in the Canadian Shield will satisfactorily ameliorate any dangers involved in summarily dismissing these oriental occurrences.

1b(ii) Definitions and Classifications

In common with many meaty geological controversies a discussion of anorthosites is not without its semantic problems and it is useful to air these at the outset.



1 Rogaland (Michot 1960).
2 Harris (Dearnley 1963).
3 Gardar (Bridgewater 1967).
4 W.Greenland (Windley 1967).
5 Nain (Wheeler 1960).
5a Kinglipait (Morse 1966).
6 Michikamau (Emslie 1965).
7 Mealy Mts. (Kranck 1961).
8 Indian Head (Hoyle & Ronan 1954).
9 Romain River (Kranck 1961).
9a Allard Lake (Hargraves 1962).
10 Sept Isles (Faessler 1942).
11 Labrieville (Anderson 1966).
12 Lac St. Jean (Kranck 1961).
13 St. Urbain (Mawdsley 1927).
14 Morin (Papezik 1965).
15 Adirondacks (Buddington 1939).
16 S.E. Ontario (Harrison 1944).
17 Duluth (Taylor 1964).

Fig 1-1. Locality of Map Area and Distribution of Some Major Anorthosites.

The name anorthosite itself was apparently coined by Hunt (1857, p.22) for the plagioclase-rich rocks of the Morin series of Quebec, but not through ignorance of the anorthite content of the plagioclase since anorthosite superseded such terms as "lime-feldspar rock" and "andesine rock" used, for the same rocks, by Logan some years earlier. It is interesting to note that Osborne (1956) suggests that Logan was influenced by Hunt, a Wernerite, to ascribe a sedimentary origin to the Morin anorthosite; but no doubt he was also impressed by the laminated plagioclase crystals apparent in many outcrops. However, Selwyn (1877-78, p.12A) and Adams (1897, p.91) helped to establish the igneous origin of these particular rocks, the latter noting igneous textures and the intrusive nature of the contact. In the event, for the next 40 years the term 'anorthosite' signified a plagioclase-rich, igneous rock.

In 1939, however, Buddington (p.208ff) suggested that 'anorthosite' was in fact a morphological term which encompassed within its definition two rocks of genetically distinct phylogeny. He proposed that a distinction be drawn between anorthosites that occur in layered intrusions and those that form independent, large, domical massifs. Textbooks such as Turner & Verhoogen (1960) tend to suggest that this proposal has attained the stature of a dogma[1]. It should be emphasised that this bipartite classification is based, essentially, on a genetic interpretation of the origin of the two anorthosites: however, even those who do not adhere to Buddington's views on the massif type

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[1] No pejorative connotation intended.

still agree there is a significant distinction to be made, e.g. Barth (1962), Berrangé (1965), Philpotts (1966). In this memoir Buddington (p.208) discusses several features that he suggests support this distinction and Table 1-1, after Berrangé (1965), tabulates those proposed originally by Buddington plus others considered significant by Berrange.

On the other hand, in the same memoir Buddington (p.19) defines various facies within the Adirondack massif thus:-

Anorthosite	0-10% mafic minerals,
Dioritic Gabbroic } Anorthosite Noritic	10-22½% " " ,
Diorite Anorthositic { Gabbro Norite	22½-35% " " .

To the present there has been no study in sufficient detail to accurately delimit the area of distribution of these facies within the Adirondacks or any other body and the terms seem to be restricted to use in description of specific hand specimens or outcrops.

Resulting from the adoption of Buddington's suggestions there are now several definitions appropriate to the term 'anorthosite':-

1) Morphological; defining a rock unusually rich in plagioclase irrespective of its environment. This is the original use of the term.

2a) Generic; a name for layers or bands of rock consisting of 90%

A	B
Environment	
Anorthosites and country rocks confined to high grade, upper amphibolite or granulite facies migmatite terrains of the catazone.	Any similarity in mineral facies between anorthosite-bearing stratiform complexes and the surrounding rocks is fortuitous and these plutons occur in the catazone, mesozone or epizone.
Age	
Confined to the Precambrian.	Of any age from Precambrian to Tertiary.
Form	
Plutons of varying shape and size, gently dipping sheet- or nappe-like form probably quite common. Also elongated masses with a length 10 to 100 times greater than width and intercalated with migmatites.	Lopoliths or funnel-shaped bodies most common.
Textures	
Commonly coarse-grained and very coarse-grained with plagioclase and pyroxene crystals measurable in inches or feet.	Giant crystals absent.
Ultrametamorphic granofels textures.	Typical cumulate textures.
Stress effects typical e. g. kink banding of pyroxenes, bending and/or granulation of plagioclase.	Kinematic effects absent, or fortuitous due to post-intrusion superimposed stress.
Mineralogical composition	
Anorthosite and noritic or gabbroic anorthosite predominant.	Ultramafic and mafic rocks predominant.
More mafic facies confined to the margins of the plutons.	More mafic facies predominate in lower zones. Most anorthosite in middle zones.
Compositional variations disorderly and gradational.	Regular and abrupt changes in composition of layers.
Plagioclase composition can be remarkably constant over vast areas, or can vary in either a regular or, more commonly, an irregular manner. No sympathetic variation in composition between plagioclase and mafics. Antiperthite common.	Plagioclase composition strictly governed by its position in the layered sequence and varies sympathetically with the compositional changes in the mafics.
Primary mafics either orthopyroxene, clinopyroxene or both together, olivine absent or rare. Pyroxenes commonly more or less altered to amphiboles. Garnet widespread.	Primary mafics orthopyroxene, clinopyroxene and/or olivine.
Primary accessories common — apatite and ilmenite-magnetite. No platinoid- or chromitite-bearing layers.	Accessories rare. Layers enriched in the platinoids or chromite are characteristic.
Internal structures	
Largely massive and structureless, where layering present it is commonly associated with kinematic foliation or some ultrametamorphic process rather than a simple magmatic cumulate process.	Characterised by rhythmic layering, cryptic layering, phase layering, inch-scale layering and igneous lamination-structures indicative of magmatic differentiation under stable conditions.
Cognate inclusions of more feldspathic rock in more mafic types are common.	Comparable block structure is uncommon.
Anorthositic satellites	
Satellites common around the larger "equidimensional" bodies.	Anorthosite satellites not found.
Gravity measurements	
Negative gravity anomalies.	Positive gravity anomalies.
Associated Salic Rocks	
Anorthosite associated with green pyroxene-perthite-bearing salic rocks of ultrametamorphic to igneous aspect, i. e. enderbite, mangerite and charnockite.	Have thick caps of red granophyre, granite and/or rhyolite above the more basic types.
These rocks commonly marginal to, and can show gradational or intrusive relations into, the anorthosite-gabbro. Mobilised types probably of anatectic origin.	These rocks occur on top of the basic members of the stratiform bodies. Are definite magmatic differentiates, comagmatic with the ultrabasic and basic members stratigraphically below.
Contact metamorphic-metasomatic effects	
Widespread contact phenomena at borders of anorthositic plutons are similar to those familiarly developed around granitic bodies. Pegmatitic and hydrothermal activity extensive.	Mainly thermal contact metamorphism.
Dynamic metamorphism also widespread.	Dynamic metamorphism local.

TABLE I-I

Contrasted features of orogenic-plutonic (A) and gravity-stratified (B) anorthosites.

From BERRANGE 1965 Table I, p. 623 ff.

modal plagioclase, such layers existing as units in a larger, stratified body.

2b) *Generic*; as a term for a complete body of rock containing large domains with high modal plagioclase (>80%?) but with apparent gradation into other less plagioclase-rich domains[1], the *whole* comprising "an anorthosite". Bodies of this type are usually referred to as *massif-type anorthosites*. This is the sense in which anorthosite is used in this thesis unless otherwise stated.

3) *Specific*; as a term for a facies consisting of 90% modal plagioclase occurring within bodies of rock defined as in 2b. In this thesis this usage will be designated 'pure anorthosite'.

Now, attention is drawn to the fact that definition 2a refers to part of a larger whole while 2b is in itself a whole. Further, it is noted that 'anorthosite' is defined more strictly with respect to modal plagioclase under definition 2a than 2b; this distinction may have important implications. For example, from a few personal observations and from conversations with geologists familiar with the Bushveld and Duluth complexes it would seem that great thicknesses of both these well known bodies would be termed 'anorthosite' under the more elastic definition, 2b[2].

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[1] This definition has been left vague deliberately so that it can comfortably accommodate all the bodies of rock which various authors have in fact called anorthosites. For most of these bodies data are insufficient to quantify further.

[2] This point is particularly drawn to the attention of those personally unfamiliar with *both* types in the field.

That is, it is suggested that the two definitions tend to exaggerate some differences and/or mask some similarities between layered intrusions and massif anorthosites, without of course detracting from the weight of other distinctions between them.

1b(iii) Genesis of Anorthosite. Previous Work.

Not only are there 'anorthosites and anorthosites' as distinguished by Buddington but there also, supposedly, exist 'anorthosites and anorthosites' even within the massif type category. Several authors (Michot 1955, Barth 1962, den Tex 1965) have in fact suggested that different processes may be operative in the genesis of different anorthosites, thereby solving a (straw) anorthosite problem in the same way as the so-called granite problem. While such a solution may be valid in specific instances it is far from being a panacea. For example, there exist several, distinct theories for the origin of the Adirondack anorthosite alone and, moreover, some authors clearly intend their theories to be applicable to many, if not all, anorthosites.

Table 1-2 arbitrarily forces the extant, variegated theories on anorthosite petrogenesis into five pigeonholes, each labelled to emphasise what I consider are the crucial differences between them. It is necessary to note that some authors could, with justice, be placed in more than one category and, as should be obvious from discussion below, those in the same pigeon-hole would not necessarily unreservedly endorse the theories of their 'colleagues'.

Table 1-2 is not comprehensive in the sense of being a complete anorthosite bibliography. It omits various papers that either do not

TABLE 1-2

Classification of Theories on Anorthosite Petrogenesis

Category	Type	Author		
1	Anorthosite magma never existed as such: anorthosite is in fact a cumulate rock	Bowen	1917	Adirondacks & General
		Balk	1931	"
		Barth	1936	Norway
		Emslie	1965	Michikumau
		Bridgewater	1967	Gardar Province
2	Massif type anorthosite crystallised from magma resulting from assimilation of country rock by 'normal' magma type	Michot P.	1960, 1955b	Egersund-Ogna Massif, Norway
		Philpotts	1966	Morin
		Kranck	1961	General
3	Massif type anorthosite crystallised directly from magma of gabbroic anorthosite composition	Buddington	1939, 1961	Adirondacks
		Harrison	1943	S.E. Ontario
		Subramaniam	1956a	Kadavur Mass (India)
		Hargraves	1962	Allard Lake
4	Metasomatism & Anatexis	Hietanen	1956	Boehls Butte
		Berrange	1965	General
		Berg	1966	Bitteroot, Montana
		Michot J.	1961	Haland-Helleren, Norway
		Winkler & von Platen	1960	Experimental
5	Massif anorthosites are (in some cases) metamorphosed and disrupted layered intrusions	Subramaniam	1956b	Sittampundi Complex (India)
		Windley	1967	W. Greenland

discuss the origin of anorthosites specifically[1] (while discussing other cogent phenomena) or only refer to this problem obliquely. However, it does give an adequate survey of the various theories in the field.

Theories of Type 1

The artificial nature of the above classification has already been noted and an upshot of this is the strange bedfellows it, like politics, makes. This is exemplified by the uneasy alliance in category 1 of Bowen, Balk, Emslie and Bridgewater.

Balk, whose theories can be regarded as an elaboration on Bowen's original theory, postulated a dioritic magma in which the mafic minerals coalesced to form gabbroic masses (gabbro in statu nascendi) within the aggregation of plagioclase crystallising at the same time and that the residual syenite liquid was squeezed out of the anorthosite to form the surrounding pyroxene syenites. Emslie, on the other hand, proposes an olivine basalt magma which, with the continual separation of liquid during the crystallisation (perhaps by volcanic activity) continued to settle out plagioclase which accumulated under gravity throughout most of the solidification history: the surrounding syenites he proposes are not genetically related to the anorthosite. Finally, Bridgewater postulates an initial alkali basalt magma from which the plagioclase accumulated by flotation to the top of a magmatic chamber (a chamber in which the magma is already partially differentiated by 'liquid separation') and further differentiation produced the various alkalic rocks of the Gardar suite, which include syenites, carbonatites, granites, the Ivigtut cryolite body and the peralkaline suite of Ilimaussaq.

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[1] Many government reports come in this category.

Theories of Type 2

The unifying aspect of this group of theories is that the various authors propose a primary magma (mantle derived?) modified by assimilation of crustal rocks. This group can, in fact, be considered an elaboration of Type 1.

Michot (1955) postulates the crystallisation of a 'plagioclasic' magma, derived by assimilation of vast quantities of pelitic rocks by a basaltic magma, as the origin of the Egersund-Ogna massif - the largest of the several anorthosites recognised by him in S. Norway. He ascribes a similar magma crystallising under more complicated tectonic conditions as the parent of the Bjerkrem-Helleland-Sogndal anorthositic complex. See fig. 1-2.

Kranck (1961) suggests that during 'Grenville' times sediment accumulation and subsequent subsidence of the geosyncline were unique in their slowness giving ample time for contamination of sediments in the basaltic sub-crustal material and that the magma so produced moved upwards very slowly and crystallised over a very long period of time. (Slow cooling also considered an important feature by Barth, 1936).

Philpotts (1966) derives the Morin Series of Quebec from a calc-alkaline granodioritic magma originating through assimilation of crustal rocks by a dioritic magma. He finds it necessary to postulate a granodioritic (i.e. with assimilation) rather than a dioritic magma (in which case his theory would be similar to Balk's) to account for the large amounts of acidic material which he interprets as being co-magmatic with the anorthositic rocks. The anorthosites themselves originated by crystal accumulation, according to Philpotts, and therefore his theory

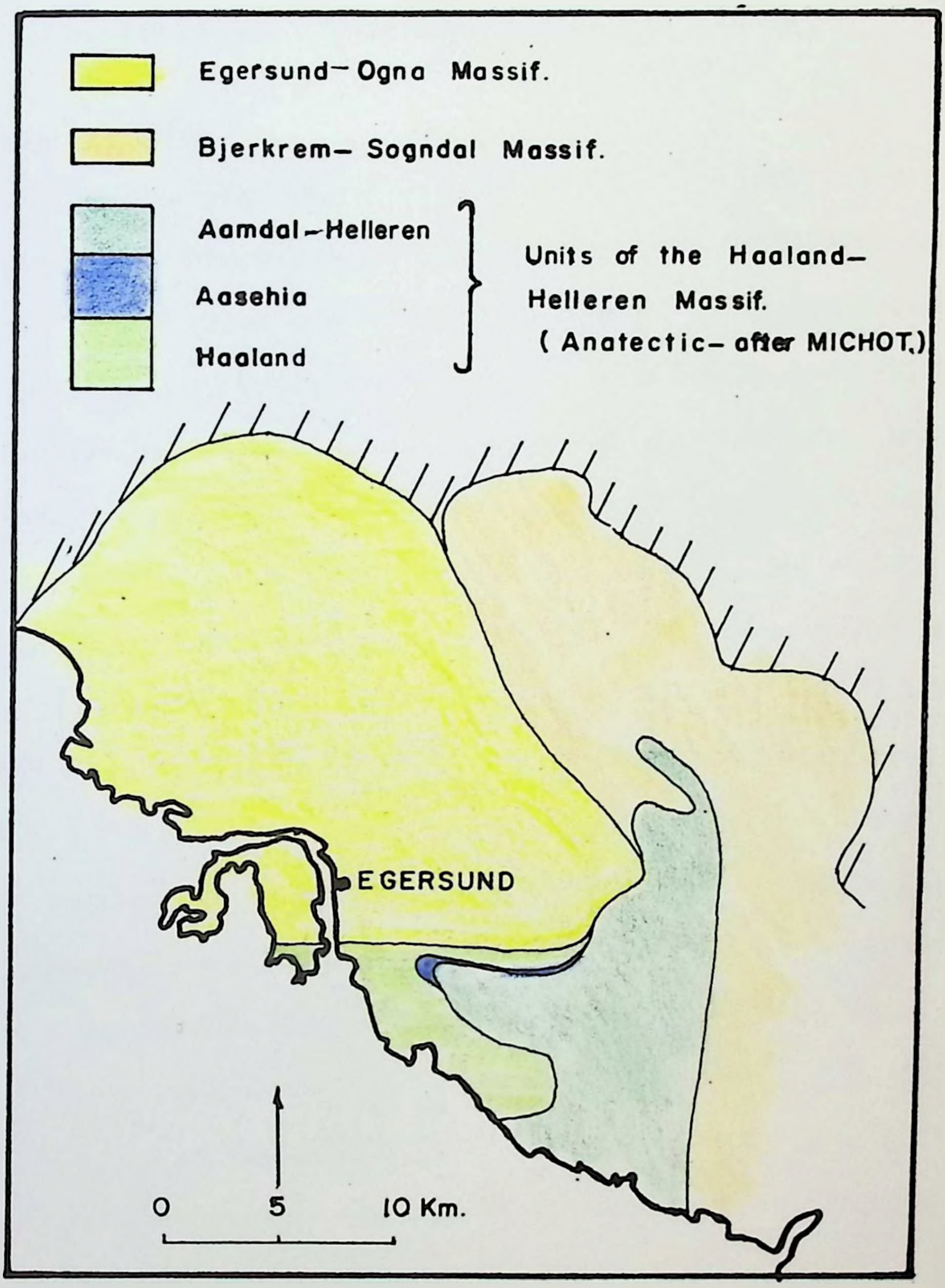

FIG.-1-2 Massif-anorthosites of the Egersund area, S. Norway (After Michot P. 1960.)

has, in this respect, affinity with those of Type 1.

Theories of Type 3

Contrasting with the groups of theories outlined above advocates of Type 3 are more unanimous in believing that the massif anorthosites are the result of crystallisation of a magma of singular composition, in fact that of a gabbroic anorthosite. This theory was originated by Buddington (1939,1961) for the Adirondack anorthosite. This magma is believed to have formed by partial fusion of basaltic or mantle material in the presence of abundant volatiles. Further, he believes that the surrounding syenite gneisses are genetically distinct from (and younger than) the anorthositic rocks. Hargraves (p.183ff, 1962) has elaborated on Buddington's theory (which had been accepted more or less in toto by Harrison (1943) and Subramaniam (1956(a)) emphasising the role of volatiles during the crystallisation. Postulating a high confining pressure he proposes that volatiles would escape outwards carrying with them the mafic constituents which are then deposited on the border of the body while the volatiles continued into the surrounding salic gneisses where they effected partial melting. Diffusion of K_2O and SiO_2 from these semi-molten rocks metasomatised the anorthosite to give rise to the contiguous pyroxene syenite.

Theories of Type 4 .

Theories of this type, involving palingenesis and anatexis, represent a radical petrogenetic divergence from theories so far outlined.

Perhaps the most heretical are the theories of Les Michots (Paul et Jean) for some of the anorthositic complexes recognised by them in

S. Norway. (See fig. 1-2). The papers Michot J. (1961), Michot P. (1955 & 1960) and Michot & Michot (1966) outline their theory in some detail, a theory involving a process called 'basic palingenesis' by Michot J. (1961) and 'processus d'anorthositisation de la norite' by Michot P. (1955).

They envisage a noritic anorthosite or leuconorite subjected to a partial fusion which preferentially mobilises the ferromagnesian minerals and some plagioclase - to form the anatectic norite, leaving behind a residium of plagioclase - the para-anatectic anorthosite. This mobilised, "dark leuconorite" - sic (Michot J. 1961, p.166) - is postulated to be capable of intrusion.

It is not clear to me what weight they place on this process as a primary origin of anorthosites. It appears, for example, that this palingenesis acts on a pre-existing leuconorite[1] (anorthosite?) and in fact Michot J. (1961, p.165) suggests that the Haland-Hellern complex (see fig. 1-2) was originally part of the more mafic border facies of the Egersund-Ogna massif which Michot P. (1955 & 1966) postulates is due to the crystallisation of a 'plagioclasic' magma (see 'Theories of Type 2' above). In Michot & Michot (1966), however, they do suggest this process is active in the crust and is responsible for an intermediate seismic layer underlying the granitic layer.

Both a dearth of quantitative, analytical data and an esoteric nomenclature in the papers referred to combine to render a brief critique of this model futile. Romey (1968, p. 233) offers an alternative reading of the evidence supporting anatexis, while I note that J. Michot (1961) lays

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[1] They don't, for example, propose that the process applies to other rock types, say gabbro or basalt etc.

great emphasis on the contrasted plagioclase morphologies in the 'para-anatectic' anorthosites and the 'anatectic' leuconorites. In the former the coarse grained plagioclase crystals have ragged, interpenetrating outlines, flexed, poorly developed twins and contain needles of rutile and pyroxene along with oxide dust. In the anatectic rocks, on the other hand, the plagioclases are smaller, have polygonal outlines, straight twin individuals and are free of inclusions. Similar, if not identical, textures are described in the Whitestone anorthosite (see chapter 5) but are ascribed to a completely different process.

For layers and lenses of plagioclase-rich rock occurring within garnet-mica schist in the Boehls Butte metamorphic complex Idaho, Hietanen (1963 & 1966) suggests an origin in metamorphic reactions of the following type:-

1) $4CaCO_3 + NaAlSi_3O_8 + 8SiO_2 + 4Al_2O_3 \rightleftharpoons Ab_{20}An_{80} + CO_2$

2) $Ab_{20}An_{80} + Na_2O + 4SiO_2 \rightleftharpoons Ab_{50}An_{50} + CaO$

3) $Ab + 2Al_2SiO_5 + 4CaO \rightleftharpoons Ab_{20}An_{80}$

4) $2Al_2SiO_5 + 6SiO_2 + CaO + Na_2O \rightleftharpoons Ab_{67}An_{33}$.

Such reactions she believes take place under conditions approximating the triple point of the Al_2SiO_5 polymorphs. In these layers both bytownite and oligoclase-andesine grains occur in the same rock.

Berg (1966) proposes an anatectic origin for small ($10m^2$ - $2Km^2$), concordant bodies of plagioclase-rich rock (95% plagioclase, 3% biotite, 2% quartz) which occur with tonalite in sillimanite-muscovite-orthoclase-biotite-oligoclase-quartz gneiss of the Belt Supergroup in the Bitterroot Range Montana. He postulates that under a $P_{H_2O} = 4Kb$ and a temperature of $\simeq 650^{\circ}$C the more albitic portions of the pelitic horizons melted to produce a tonalitic melt and an anorthositic residuum. The feasibility of such a process has been demonstrated experimentally by Winkler und von Platen (1960). Berg notes that within a given *thin-section* there is a wide range in plagioclase composition, $An_{37} \rightarrow An_{65}$. This is in sharp contrast to the remarkable homogeneity of the plagioclases in the much larger "massif" anorthosites.

The theories of Hietanen and Berg have been discussed here only for the sake of completeness since such features as the variable plagioclase composition, mise en place, and general small size serve to distinguish them from the enormous, homogeneous massif type anorthosites: that is, while the anatectic model suggested by Winkler & von Platen's work could, perhaps, be tentatively accepted for these unusual occurrences the same model for the massif-type is not warranted. A general acceptance of the origin of these bodies plus the discovery of similar occurrences elsewhere will warrant the erection of a suitable, distinguishing name for these intriguing rocks if only to forestall a semantic difficulty.

Theories of Type 5

In this category belong those theories which ascribe to some anorthosites a secondary origin in the disruption of a layered intrusion by subsequent orogeny which partially, or wholly, obliterates the traits of this type, in particular the close spatial and obviously genetic relations with ultramafic differentiates. Like Hietanen's and Berg's proposals, theories under this heading have been proposed for specific occurrences only and not as a general petrogenetic theory for all anorthosites.

The appositeness of such a theory in a particular instance depends on the recognition of distinctive structural, mineralogical or chemical characteristics. Windley (1967), for example, proposes such an origin for the anorthosites of W. Greenland (Sorenson 1955, Ellitsgaard-Rasmussen & Mouritzen 1954) on the basis of abundant chromite horizons[1] and the presence of persistent phase and inch-scale layering. A similar origin has been ascribed to the chromite-bearing Sittampundi complex (Subramaniam 1956b) and the Sakeny anorthosite in Madagascar (Boulanger 1957).

Anorthosites and ~~Anorthosites~~

Contrasting with the schismatic classification due to Buddington which has coloured orthodox teaching on anorthosite genesis, some current writings on this subject have proposed a more ecumenical approach suggesting that too much emphasis has been placed on the differences between layered intrusions and massif anorthosites and not enough on their similarities. Such arguments do not fit into the arbitrary classification outlined above since it applies only to massif anorthosites.

Romey (1968) proposes "the existence of a full spectrum of anorthosite types (which) suggests a gradation in conditions of their formation rather than any sharp discontinuity in processes". His reasoning is based mainly on the recognition of structures in an incipient or subdued state in massif anorthosites which, in full bloom, are characteristic of layered intrusions. Igneous- (or gravity-) layering and cumulate

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[1] While common in layered intrusions of Bushveld type chromite appears to be absent in all massif anorthosites.

textures are prime examples of such structures. The similarity in structural state, and spectrum in composition, of the plagioclase in the 2 types which he uses as supporting evidence, is of more doubtful significance. Romey, himself, does not propose any synthesis linking the two types.

Middlemost (1968) on the other hand, proposes that the seeming dichotomy between the two is to be attributed to physical processes during emplacement and crystallisation rather than to initial, radical chemical differences. Briefly, he suggests that layered intrusions were emplaced and crystallised in rigid, stable envelopes while the typomorphic massif anorthosites were emplaced in a more mobile, catazonal envelope which varied in geometry during crystallisation. He proposes that the mafic differentiates of this latter magma plunge down towards the mantle[1] due to their high S.G. arguing that if light material such as salt and acidic magma can punch upwards in diapirs then heavy material can equally well plunge downwards. It should be noted that the lack of an exposed mafic zone and lack of gravimetric evidence of such heavy differentiates in massif anorthosites (Simmons 1964) is often used as the most telling evidence arguing the existence of two groups of anorthosite and that many authors have, in effect, premised their arguments on the real absence of such differentiates, (i.e. such differentiates never existed).

A more eclectic synthesis of the anorthosite lineage has been forwarded by Berrange (1965). He accepts the two types of anorthosite à la Buddington but erects an 'anorthositic series' à la H.H. Read, to

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[1] Before complete solidification.

categorise three broad groups of anorthosite previously lumped under massif anorthosites.

He envisages that during periods of maximum downbuckling of the orogen autochthonus anorthosites form in situ by metasomatic-metamorphic reconstitution of original supracrustal rocks to form anorthositic layers interbedded with high grade metamorphic rocks (à la Hietanen and à la Berg). As examples of this type he proposes the anorthosites of W. Greenland, of the Bergen arc (Kolderup 1933) and those of Boehls Butte[1].

With increasing temperature more rock types are affected, mobilising granitic and leuconoritic liquids, leaving an anorthositic residuum (à la Michot) to form the para-autochthonous anorthosite type.

Thirdly, Berrangé suggests that at temperatures circa 1000° C this para-autochthonous anorthosite is itself fluxed and during the concomitant orogenesis is induced to intrude to higher levels to form the anorthosite plutons.

1b(iv) A Pot-pourri of Isotope Data and Associated Theories

Various lines of isotopic evidence have been admitted to help unravel the complexities which arise from the variegated interpretations of the field evidence, unfortunately without clearing the way (at least on the face of it) but hopefully this may prove to be in large part faulty interpretation - and not wholly by the isotope geochemists.

Age Dating

Completely lacking zircons[2], the anorthosite itself is not amenable

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[1] Windley (1967), however, argues that the first two are both disrupted layered intrusions.

[2] It does, however, contain abundant sphene but it is unknown if it contains enough radioactive material

to the well-known U/Pb method; similarly, a poverty of Rb plus an enrichment of Sr prevents a spread of Rb/Sr sufficient to erect an isochron being obtained from true anorthositic rocks. Foiled on a direct approach, the problem has been attacked by dating rocks supposedly genetically related to the anorthosite and thus, inferentially, coeval with it.

Silver (1966), using a U/Pb method on a zircon suite, reports an apparent age of 1125 ± 10 m.y. for the pyroxene-syenites contiguous on the Adirondack anorthosite (see fig. 4-5 p.121). These rocks, in contrast to other Adirondack rocks, show no 'memory' of an older age. The age of 1125 m.y. is presumably that of intrusion and is analytically distinct from the metamorphic age of 1090 ± 10 m.y. obtained from the surrounding gneisses. Heath (1967), using essentially the same syenites as Silver, reports an age of 1055 m.y.[1] (using Sr $\frac{87}{86}$ whole rock data) - nearer to the U/Pb metamorphic age. It would normally be assumed that a Sr $\frac{87}{86}$ whole rock would also give a pre-metamorphic age and this discrepancy is puzzling[2]. It is pointed out that the relevance of these ages to that of the anorthosite is based entirely on the comagmatism of the syenite and the anorthosite; this remains controversial!

Initial Sr $\frac{87}{86}$ and Rare Earths in Anorthosites

Commenting on this problem, Heath (1966) suggests that the initial Sr $\frac{87}{86}$ ratio of the Adirondack anorthosite (0.7049 ± 0.0003) is analytically similar to the initial ratio (0.7055) of the syenites, a relation which is consistent with, but far from proves, their consanguinity. On purely

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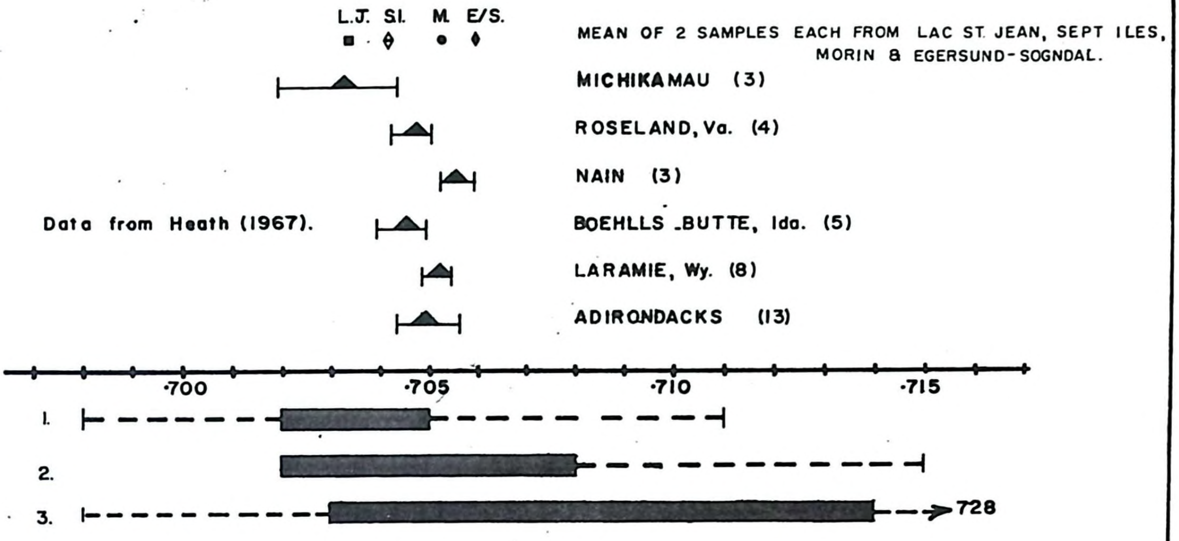
[1] This is using geologically deduced $\lambda = 1.37 \times 10^{-11}$; counting indicates more suitable decay constant is $\lambda = 1.47 \times 10^{-11}$ which would give age of approx. 1000 m.y.

[2] An attempt to reconcile these dates by changing their interpretation is made in Section 4g, Chapter 4.

FIG. 1-3 Initial Sr 87/86 in some anorthosites.

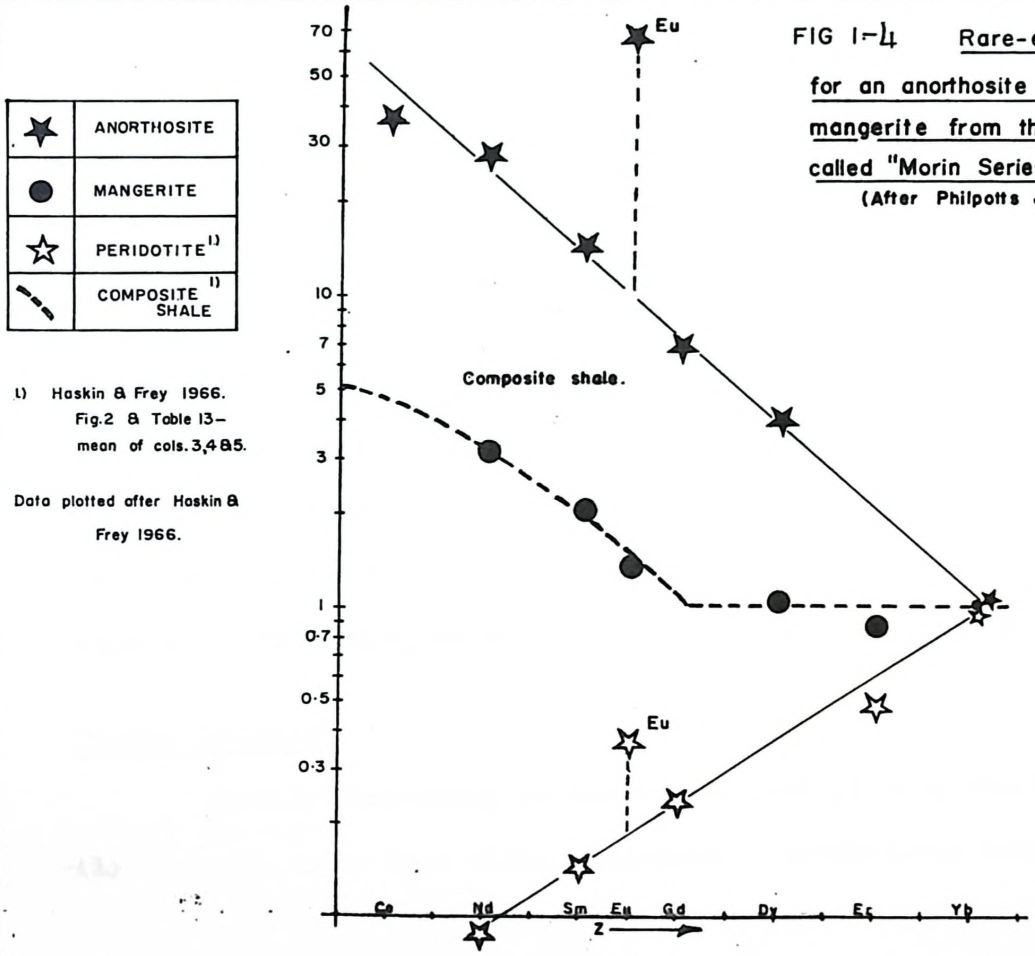


Data from Heath (1967).

Absolute and modal range of initial Sr 87/86 of three rock types for comparison.

1.– Oceanic basalts
2.– Continental basalts
3.– Limestones

FIG 1-4 Rare-earth data for an anorthosite and a mangerite from the so-called "Morin Series."
(After Philpotts J.A., 1966)



1) Haskin & Frey 1966. Fig.2 & Table 13– mean of cols. 3,4 & 5.

Data plotted after Haskin & Frey 1966.

isotopic grounds it is equally likely that this is fortuitous, since many common basic rocks have initial ratios in the range 0.7040 to 0.7055, see fig. 1-3. Confirming this, Heath goes on to note that the initial ratios of anorthosites are similar to those of continental basalts but are not consistent with an origin by metamorphism of anatexis of marls or limey-shales since, in this case, ratios would be expected to be in the range 0.7050 → 0.720 (that of marine limestones and shales, respectively, 2 b.y. ago). Returning to the anorthosite/acidic rock question, Heath notes that the initial ratios of the adamellites of the Nain region are far higher than that of the anorthosite they surround, thus appearing to rule out a direct lineage in this case.

Contrasting the features of rare-earth abundances (determined by stable-isotope dilution techniques) in the Morin anorthosite and spatially related mangerite, Philpotts J. et al (1966) concludes that, while the anorthosite has rare-earth abundances typical of a crystal cumulate from a basaltic liquid, the mangerite belongs to either a separate differentiation sequence or, if from the same liquid, it has been severely contaminated by other rocks subsequent to the separation of the anorthosite giving the mangerite an overall sedimentary-type cast of rare-earth. In particular the large europium anomaly in the anorthosite is contrasted with the normal europium value in the mangerites, see fig. 1-4.

Oxygen Isotopes

Equally intriguing is the oxygen isotope data presented by Taylor (1966). He notes that while some massif anorthosites (viz. Egersund, San Gabriel, Calif., and Lac St. Jean) and some layered complexes (viz. Bushveld, Stillwater and Duluth) have δ^{SMOW}-values ranging from 5.8-7.5‰

similar to that of gabbros and basalts, the Adirondack anorthosite has an atypically high $O\frac{18}{16}$ ratio ($\delta = 9.1 \rightarrow 11.2$ ‰, 28 samples). Taylor attributes these to an isotopic re-adjustment consequent on the "intense metamorphism" undergone by the anorthosite in which the metasediments acted as a source of high $O\frac{18}{16}$ fluids which were continually flushed through the anorthosite. Such a mechanism seems to imply the breakage and rejoining of large numbers of Si-O bonds.

1c. Discussion on Anorthosite Genesis

Being primarily concerned with the origin of the Whitestone anorthosite it is not my intention to pronounce on the genesis of anorthosites in the round[1] and I admit that the foregoing synopses, while hopefully falling short of libel, are sketchy and do not do proper justice to their proponents. Nevertheless, since all possible origins for the Whitestone body consistent with the data must be considered these existing theories have been introduced in this leading position to set a frame of reference.

The calibre of the controversy over anorthosite petrogenesis is underlined by the number and diversity of the above hypotheses. Such diversity implies, superficially, either that only one is correct or that anorthosites have evolved under several independent and divergent physico-chemical conditions. A third possibility is that none of the proposed theories are wholly correct as they stand, the origin of anorthosites being, in fact, dependent on a rather restricted set of physical conditions:

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[1] Nevertheless I retain a certain licence to comment where appropriate.

that is, the similarities of anorthosites are a result of these physical conditions and the differences between them being traced to variations in their chemistry. The intuitive reasonableness of this proposal is suggested by the nature of the differences and similarities:

Similarities

a) Invariably large bodies;

b) Plagioclase predominates greatly over any other phase;

c) The constituent minerals are amazingly homogeneous, both in themselves (i.e. unzoned) and over the body as a whole - see Chapter 5 and 6;

d) A late stage iron-titanium-rich fluid (magma?) is developed - I see this as a corollary of (c);

e) Known occurrences are restricted to a Pre-Cambrian age; this is easily equated with great depth.

Differences

a) Variability in composition of the plagioclase - from An_{35} to An_{65};

b) Variability in type of mafic phase. E.g. In Allard Lake this is orthopyroxene while in the Whitestone anorthosite it is clinopyroxene; the Michikamau is unique in having olivine as a major phase;

c) Variability in the nature of the secondary or accessory minerals - in the Whitestone body scapolite is common but is rare to absent in other bodies; similarly, apatite is a common accessory in the Adirondacks but is very rare in the Whitestone body (see Chapter 5).

I propose that it is easier to envisage the differences being imposed on the similarities rather than vice versa. On the basis of this thesis, then, the problem partly devolves to identifying the appropriate physical conditions. Now, while this polyphyletic approach offers a desirable flexibility in explaining the differences while accounting for the similarities, it does not automatically solve or lessen all the controversies existing in anorthosite petrogenesis. However, the preceding sections have been useful in underlining the controversial points and indicating the type of data that can be most profitably examined in the present study. The following points are what I see as the crucial problems and the data presented in the following chapters will be displayed to best illustrate its relevance as evidence on:-

1) the relation of the anorthosite to the surrounding rocks;
2) the relative importance of igneous and metamorphic processes;
3) differentiation trend(s) in the anorthosite;
4) manner and (hence) the physical conditions of crystallisation of the anorthosite;
5) primary composition of the magma;
6) relative age of the anorthosite and metamorphism.

Obviously some, if not all, of these problems are inter-related and they cannot all hope to be solved with equal certainty; however, it is hoped that having outlined them here will be useful to the general reader.

CHAPTER 2

THE FIELD GEOLOGY OF THE WHITESTONE ANORTHOSITE

2a. Introduction

In this chapter the field evidence bearing on the geology of the Whitestone anorthosite will be marshalled and briefly discussed.

The particular exposition used in this thesis is predicated on the belief that studies concerning natural rocks involve such a host of theoretically possible observations, many of which are probably irrelevant within the study's terms of reference, that it is not feasible to approach strict objectivity in the presentation of the data. This being so, the data presented in this chapter will be presented so as to emphasise those features which, because of their postulated significance, are supposed most illuminating.

It is of course the collection and sorting of the field data that involves the most subjectivity. The credentials of the author as an 'expert witness', and therefore justifiably subjective, are based on nine months association with the Whitestone anorthosite in its natural habitat and it will become apparent that the initial impetus for many of the views proposed derived from this familiarity.

The results of these nine months[1] are condensed, edited and displayed as Map I (in back pocket).

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[1] Spread over three field seasons.

2b(i) Exposure and Access

Exposure[1] is good to excellent over the bulk of the anorthosite, outcrops continuous over several hundred square yards being common in the central parts of the anorthosite. On the other hand, as is common at interfaces of rocks with distinct physical properties, the contact of the anorthosite with the country rock is only patchily exposed. However, the contact can usually be defined to within a few tens of yards while Snakeskin Lake, Lac du Bois, the Whitestone River, the three arms of Whitestone Lake, and Lake Shawmaga all give perfectly exposed sections across the contact, and, as a bonus, pleasant access to the pluton.

While exposure of the Lac du Bois formation (see Map I and Chapter 3) is adequate, the outcrop area of the Whitestone Lake formation includes only a few good exposures, probably due to the abundance of marble in this unit.

The general area itself is easily reached by Highway 124 from either the Trans Canada Highway 69 at Parry Sound, or Highway 11 at South River. Within the area, roads for the most part circle the barren anorthosite outcrop, but both Shawmaga Lake and Lorimer Lake roads give partial access while, as noted above, the many E/W Lakes are useful access routes to the interior of the body.

2b(ii) Previous Work in the Whitestone Area

Hitherto the area has not been a fashionable 'Grenville' locale so that only a few general surveys which include the Whitestone area are

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[1] Areal extent of bare-rock exposures visited during the mapping are outlined by a fine dotted line on Map I.

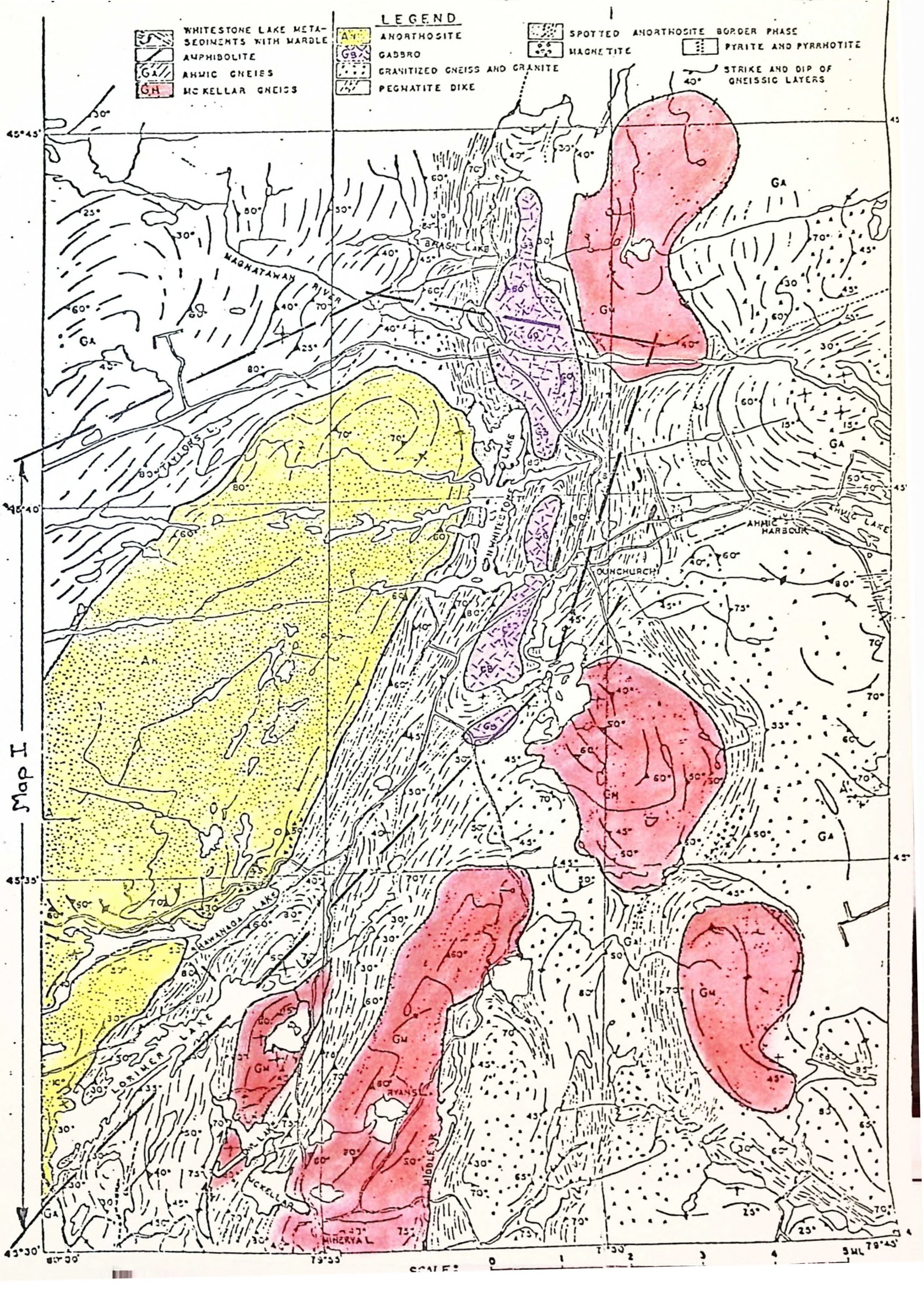
extant in the literature.

As early as 1854 A. Murray noted the presence and attitude of various 'granitic' gneisses along the Magnetawan River, and drew special attention to the marble outcrops of Maple Island and in 1913 T.L. Walker published a guide book to Parry Island describing various lithologies present there.

Of more direct importance is the mapping done by W.C. Lacy in 1940 in an area centring on the village of Dunchurch; his map, divers analytical data and brief synthesis were published 20 years later as a short note, (Lacy 1960). At the same time Satterly visited and evaluated known mineral prospects in Parry Sound District: his report, published in 1942, naturally concentrates on these showings but also includes such details of the regional geology as could be culled from roadside exposures. To the present this obviously incomplete map contains the only regional data available for that large Grenville area lying south of French River and between Georgian Bay and the Haliburton Highlands.

In 1955, as an adjunct to the Aeromagnetic Survey flown in 1953 for the Ontario Department of Mines, Satterly published a 2"/1 mile map and report of Lount Township, some 10 miles east of the present area. In this report Satterly was particularly interested in the many iron-oxide showings in the area but a survey of the general geology is also included.

A comparison of Map I and Lacy's map (reproduced here as Fig. 2-1) shows, as might be expected, a similarity in gross features. However, since the present thesis will develop ideas diverging from those


LEGEND
WHITESTONE LAKE META-SEDIMENTS WITH MARBLE
AMPHIBOLITE
GA AHMIC GNEISS
GM MCKELLAR GNEISS
AN ANORTHOSITE
GB GABBRO
GRANITIZED GNEISS AND GRANITE
PEGMATITE DIKE
SPOTTED ANORTHOSITE BORDER PHASE
MAGNETITE
PYRITE AND PYRRHOTITE
STRIKE AND DIP OF GNEISSIC LAYERS
45°45'
45°40'
45°35'
45°30'
80°00'
79°55'
79°50'
79°45'
MAGNATAWAN RIVER
BRASH LAKE
TAYLORS L.
WHITESTONE LAKE
AHMIC LAKE
AHMIC HARBOUR
DUNCHURCH
KAWANAGA LAKE
LORIMER LAKE
RYANS L.
MIDDLE L.
MCKELLAR
MINERVA L.
SCALE: 0 1 2 3 4 5 MI.

Map I

of Lacy it is meet to consider his alternative.

Lacy distinguishes between what he calls dome-forming rocks, ranging in composition from anorthosite to granite, and the metasedimentary rocks which he assigned to the "Grenville Series" on a lithologic and (presumably) geographic basis.

The "Grenville Series" he divides into:-

(?Upper?) Whitestone Lake Metasediments	Rusty weathering gneisses and garnet amphibolites interbanded with marble. Sporadic quartzites occur in the gneisses.

Contact relations undefined but dips generally concordant

(?Lower?) Ahmic Gneiss	Light coloured, well bedded gneisses ranging from mica schist to microcline feldspar gneiss.

Metamorphism is assigned to the amphibolite and granulite facies (without defining their distribution). These metasediments, he concludes, occur in "tight, isoclinally folded synclinal troughs" which resulted from the shouldering upwards of the largely solidified dome-forming rocks. Although he does not discuss the petrogenesis of the dome-forming, igneous rocks as such, Lacy appears to consider them a consanguinous lineage. Moreover, in the light of the conclusions of the present study, it is salutary to consider his interpretation of the field relations of the igneous and metasedimentary rocks. The penultimate paragraph of his paper reads:-

> "Microtextures showing crushing and regrowth of the minerals in the dome-forming rocks suggest that these rocks assumed their present position by flow in a nearly solid state. Lack of reaction with, or metamorphism of, the marble-metasedimentary unit immediately adjacent to the dome-forming rocks is indicative of either equilibrium between the rock types or other conditions not favouring reaction. In the crest portions of the dome structures, where tension conditions existed, there resulted a concentration of hyperfusible components that effected granitisation of the metasedimentary rocks."

2c. The Whitestone Anorthosite

At the outset it is probably useful to the reader to anticipate a later section on petrography to establish the following general data:-

Plagioclase is the most abundant phase in the anorthosite and has an average grain size of 3-5 m.m. with occasional dark blue or purply grains up to 20 m.m. Scapolite is common as an alteration of plagioclase.

The main mafic phase is clinopyroxene; uralitic amphibole is ubiquitous.

Apatite, oxides and associated sphene are restricted to an accessory role, except locally.

Garnet and epidote are restricted in distribution as discussed below.

In this section evidence will be introduced to support the following postulates:-

1) The anorthosite crystallised from a magma.
2) Plagioclase was the main liquidus phase during most of the crystallisation with clinopyroxene crystallising interstitially.
3) At several minor stages, mainly towards the end of crystallisation, clinopyroxene became more prominent as a liquidus phase giving rise to an igneous banding.
4) Localised movement within the body disrupted this banding to give rise to 'block-structure'; such movement occuring before complete solidification.
5) Towards the end of crystallisation an iron and volatile-rich

fluid was present in the pluton.

6) The distribution of epidote and garnet are compositionally controlled.

These conclusions are introduced here in the hope that they will serve as beacons in the necessarily descriptive passages that follow.

2c(i) Facies of the Anorthosite

Contrasting with the dark-coloured feldspars that predominate in such classical anorthosites as the Adirondacks, Morin and Lac St. Jean, the Whitestone anorthosite is a credit to its name with the plagioclases weathering a white or light grey. Due to this light colour the textures of the black mafic minerals are easily recognised, and on the basis of these textures, the body can be conveniently divided and mapped as two, main, significant facies - the glomeropoikilitic and the porphyritic. Superimposed on these two primary types are a further three secondary facies, viz. the Green Feldspar facies which occurs in the core of the exposed anorthosite, and the two marginal, foliated facies characterised by the presence of garnet or epidote. See Map I.

I. Glomeropoikilitic Facies

This facies is by far the more abundant of the two primary facies. Over and above the distribution indicated on Map I virtually all the Green Feldspar facies and much of the garnet- and epidote-bearing facies can also be recognised of this type. Locally, however, a well developed foliation precludes recognition of the pre-existing texture.

The term 'glomeropoikilitic' was selected for this texture to emphasise the unusual morphology, to distinguish it from the porphyritic facies, and to intentionally suggest an igneous origin for the texture.

For convenience it will frequently be abbreviated, as for example in "glomero-anorthosite".

In this usually massive rock the black pyroxenes occur in blotchy, sub-spherical globules or glomerules, each globule being charged with subhedral plagioclase grains, and the globules themselves are broadcast through the otherwise light grey rock in a polka-dot pattern. Typomorphic of this facies are the rocks figured in plates 2-1, 2-2 and 2-3.

Now, it is in qualitative features only that the illustrated rocks are typomorphic; in all quantitative features there is variability over the body: that is:-

1) The glomerules themselves vary in diameter from 1-10 cm.
2) The pyroxene/plagioclase ratio within the glomerules varies from 0.4-0.75.
3) The distances between glomerules varies from 1-15 cm. (rarely much more).

However, within a typical outcrop (say several tens of square metres) each of these variables maintain a relatively constant value. Exposures such as Plate 2-4 suggest that the glomero-anorthosite may be banded with respect to these quantitative variables, but it did not prove possible to elaborate on this hypothesis.

Towards the margins of the anorthosite this facies gradually passes into the marginal foliated facies, the glomerules becoming elongate (Plate 2-3) and, locally, the anorthosite has the aspect of a typical gneiss. At a few favourable localities within the marginal facies it appears that the deforming stresses were such as to produce flattening rather than shearing. That is, on surfaces normal to the

Plate 2-1 Glomeropoikilitic anorthosite, N. of Shawanaga Lake. Leaf is 4" in diameter.

Plate 2-2 Glomeropoikilitic anorthosite, N. shore of Snakeskin Lake. Note differences between 1 and 2 in size and distribution of glomerophenocrysts.

Plate 2-3 Weathered slab illustrating elongation and beginning of inosculation of distinct glomerophenocrysts as rock develops foliation. Locality of specimen 261 - see Map 2a.

Plate 2-4 This outcrop suggests that the glomeropoikilitic facies may in fact be composed of bands or layers, in general on a larger scale than illustrated here, reflecting variation in the conditions of crystallisation. N. shore of Snakeskin Lake.

It is significant to note that dip in this exposure is parallel to that shown in Plates 2-9 and 2-10 (i.e. to the West) and this is almost normal to that of the easterly dipping marginal foliated rocks.

foliation the glomerules are elongated and anastomosed to define the foliation, while within the plane of foliation the sub-circular, non-oriented section is maintained.

Glomeropoikilitic Textures in Other Anorthosites

It is here proposed that the glomeropoikilitic facies is an unusual, exaggerated manifestation of the typical poikilitic[1] or ophitic texture so common among basic rocks, noting that such textures are conventionally taken as proof of the igneous origin of the rock containing it.

In descriptions of other anorthosites poikilitic or ophitic textures are occasionally noted but rarely stressed.

For example:-

Adirondack Anorthosite: "........ pale green to purplish granular feldspar with small blotches in which the mafic minerals show an ophitic pattern ...." Buddington 1939, Table 3, No.10.

Allard Lake Anorthosite: "The bronzite crystals have several modes of occurrence .... 1) As medium to coarse-grained crystals or crystal framework, poikilitically enclosing plagioclase (Pl.3, figs. 1&2) ...." Hargraves 1962, p.166.

Morin Anorthosite: "It (orthopyroxene) occurs interstitially to the plagioclase and the rock has a sub-ophitic texture."

Philpotts 1966, p.14.

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[1] There is no conventionally accepted definition discriminating the terms ophitic and poikilitic; often they appear to be used as synonyms. However, in other cases it appears that if host phase is fairly compact with but few guest crystals then texture is ophitic, while if host crystal is larger and more disperse with many included individual guest crystals then texture is poikilitic. (c.f. Wager 1961)

St Urbain Anorthosite: "In the norite fragments the feldspar individuals are euhedral and are partly enclosed by individuals of hypersthene which form as much as 20% of the rock and attain diameters as great as 4 inches." Mawdsley 1927, p.19.

Kranck, who has studied anorthosites from many parts of the world, states:-

> "One feature characteristic of gabbroic anorthosites, but seldom mentioned, is a coarse poikilitic texture with large agglomerations of entwined mafic minerals with inclusions of feldspar .... This feature is usually overlooked because it cannot be observed in unpolished specimens." Kranck 1961, p.315.

It may well be that the singularity of this texture has not been fully appreciated by previous workers because the distribution of black pyroxenes are drowned, to the eye, in the very dark plagioclases prevalent in larger anorthosites; a thin section, while indicating an ophitic texture, is not large enough to give the complete picture. In any event Kranck alone has emphasised its possible importance in an interpretation of the origin of anorthosites.

II. Porphyritic Facies

This facies is characterised by a more homogeneous distribution and, in general, a slightly higher average modal abundance of pyroxene than the glomeropoikilitic facies. Instead of being dispersed in scattered glomerules the clinopyroxenes appear in hand specimen as distinct, generally stubby, black crystals scattered evenly throughout the rock. In general there is no obvious orientation of these grains in the rock.

This facies is much more restricted in distribution than the glomero-anorthosite, apparently occuring as bands or zones within the body and is especially prevalent near the margins. Where present over several outcrops the facies is distinguished on Map I; however, as discussed below, other smaller developments of this facies also occur.

In most cases the contact of porphyritic with glomero-anorthosite is not exposed, an outcrop often being wholly one or the other. Moreover, in cases of relatively small developments, an outcrop largely composed of normal glomero-anorthosite typically contains an irregular, larger or smaller mass of porphyritic anorthosite with nebulous contacts (Plate 2-5 and see below under Block Structure). Such masses are usually less than 5 metres in their largest dimension.

It is, however, other outcrops which show this contact of the two facies that are most illuminating regarding the origin of the porphyritic facies. In such cases the junction is seen to be abrupt, with a marked enrichment of pyroxenes in the porphyritic facies at one of the contacts. This enrichment generally persists for only a few inches before passing into a typical porphyritic facies rock. Plates 2-6 and 2-7 illustrate such contacts.

An easily accessible exposure that conveniently shows a development of the porphyritic facies more completely than usual and which throws further light on the origin of this facies, is the large outcrop due north of Bella Island in Shawmaga Lake, see fig. 2-2.

This outcrop is predominantly of typical glomero-anorthosite but it contains two zones of porphyritic facies anorthosite (2 and 4 in fig. 2-2 and 2-3). Significant features that can be noted at this locality are:-

1) Pyroxene enriched "base" to both these zones; Plate 2-6 is of

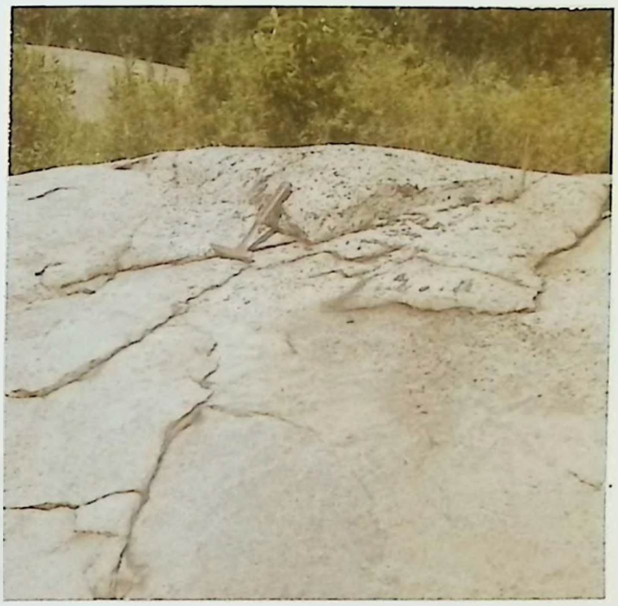

Plate 2-5 Vaguely outlined patch or 'block' of porphyritic facies (below hammer) set in almost pure anorthosite. N. bank of Whitestone River. Compare sharply delineated 'block' in Plate 2-11.

Plate 2-6 Interface of glomeropoikilitic and porphyritic facies due N. of Shawanaga Lake. Note irregular mafic enriched 'base' of porphyritic facies.

Plate 2-7 Similar interface on Whitestone River at exit from Whitestone Lake. Direction of 'younging' is identical in both 2-6 and 7 although separated by some 7½ miles.

Cross cutting pure feldspar band is strongly sheared and contains garnet. Note small fault affecting base does not affect this band.

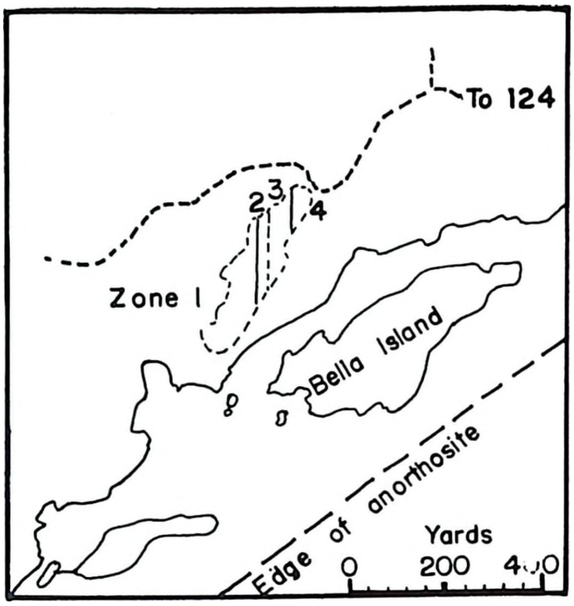

Fig 2–2 Sketch map showing locality and distribution of zones discussed in text.

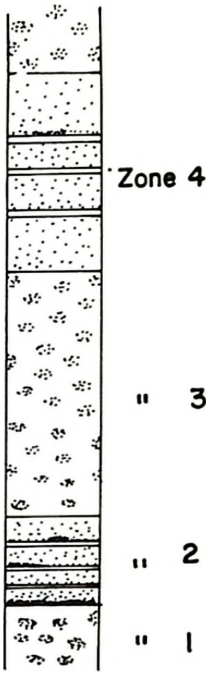

Fig 2–3 Diagrammatic columnar section through zones.

Plate 2–8 Showing band of mafic-free anorthosite within zone 2.

such an interface, but this initial enrichment grades rapidly into less mafic rock (Felsic/mafic = 80/20) which thereafter remains relatively constant within the zone. In detail the contact is irregular with minerals interlocking across the boundary. The zones extend at least 50 metres along the strike. Zone 2 is approximately 10 metres and zone 4 approximately 30 metres wide.

2) Both zones contain several, 25-50 cm. bands of mafic-free anorthosite, see Plate 2-8.

3) Commonly (but not ubiquitously) moderate pyroxene-enrichment occurs locally in the porphyritic anorthosite "above" these pure feldspar bands.

4) There is compatibility of 'bottoms' in all cases.

5) Banding strikes at high angle to edge of anorthosite, see fig. 2-2.

Equally significant is the more restricted yet persuasive outcrop exposed on Snakeskin Lake and illustrated in Plates 2-9 and 2-10. In this exposure three parallel bands of graded, porphyritic anorthosite, ranging from 15-50 cm. thick, occur in glomero-anorthosite. In this case the development of banding is more restricted since it cannot be traced 50 metres to the next outcrop across the lake. Nevertheless, it is noted that 'bottoms' of the three bands are again compatible and, moreover, the westerly dip is consistent with the nearby mafic-free bands occurring in glomero-anorthosite which are illustrated in Plate 2-4. It may be of structural significance that the westerly dip in both these outcrops is at variance with the regional easterly dip of the marginal foliation.

Plate 2-9 Outcrop suggestive of igneous layering on N. shore of Snakeskin Lake. Three bands visible are all parallel.

Plate 2-10 Close-up of central band of 2-9.
Note - lower and upper contacts parallel but irregular in detail; no obvious lamination of pyroxene or plagioclase.

Two further, widely scattered outcrops identical to Plate 2-10 have also been discovered in the pluton.

It is proposed here that such field relations support the hypothesis that at some stage(s) during the crystallisation of the anorthosite conditions in the magma fostered the differential gravitational settling of the two main crystallising phases, pyroxene and plagioclase, resulting in the banding in particular and the porphyritic facies in general. Wager & Deer (1939) and Hess (1960), among others, have persuasively argued that magmatic conditions favouring development of banding involve an interaction of such variables as differential S.G. of crystallising minerals and liquid, and strength and direction of (local) magmatic currents. Chapter 7 (pp.125-137) of Hess (1960) gives an appropriate theoretical discussion of the origin of layering.

Unfortunately, various later events such as late stage movement (see Block Structure) and pervasive recrystallisation of minerals (see Petrography) have masked or obliterated much of the original data so that it is not possible at the moment to discuss the origin of the banding in a more quantitative way. Nevertheless, this does not detract from the importance of having established the presence in this anorthosite of layering similar to that found in many other slowly-cooled plutons ranging in composition from ultra-basic to acidic. (See various papers in Symposium on Layered Intrusions 1962).

Block Structure

It has been noted above that the porphyritic facies is more restricted than the glomeropoikilitic and also that it is much more common near the margins of the pluton. It is possible that the marginal foliation, where strongly developed, hinders recognition of further developments of this facies. However, also relevant to this point is the phenomenon of 'block-structure'.

This structure, named by Balk, seems to be a prominent feature of the Adirondack (Balk 1931, Buddington 1939) and St. Urbain (Mawdsley 1927) bodies, and may be as yet unrecognised in other less thoroughly studied bodies[1]. Of this structure Balk writes (1931, p.357-358),

> "Such rocks consist of a multitude of round or angular blocks of anorthosite surrounded by anorthosite of a slightly different character .... The boundaries of such blocks may be sharp on one side and elusive or even invisible on the opposite side .... Near the contact zone of the anorthosite massif the groundmass is often foliated, and this foliation swings concordantly around the contours of the blocks. In size the measured blocks range from $\frac{1}{2}$ foot to over 30 feet."

Buddington notes that in most cases the enclosing rock is more mafic than the included block (but allows the reverse also occurs), and moreover, the structure seems to be restricted to the border facies of the anorthosite. Buddington uses the fact that the blocks are usually less mafic than the matrix to buttress his thesis that "the order of succession (of rock types) is definitely from anorthosite to saturated gabbro or norite." (Buddington 1939, p.215)

In the Whitestone anorthosite blocks of this nature also occur, especially in rocks near the border. Plate 2-11 figures a good example of this genre from a locality near Sterling Green's farm on the Shawanaga Lake road - a locality particularly rich in this feature. In this case, and others in the vicinity, the block is more mafic than the host and, moreover, note that the block is of Porphyritic Facies while the host is

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[1] Harrison, however, specifically notes its absence in the small S.E. Ontario masses. Harrison 1944, p.1409.

Plate 2-11 Sharply delineated block of porphyritic facies in glomero-anorthosite. Note swirl of glomerules round block at left. N. of Shawanaga Lake road at Sterling Green's farm.

Plate 2-12 Foliated epidote facies of western margin of body. Note lack of any small-scale folding and compare with Plates 3-1 and 2.

of Glomeropoikilitic Facies. However, in other localities blocks of pure anorthosite are found in a more mafic matrix.

North of the Shawanaga Lake Road (due North of Bella Island, see fig. 2-2) there is strong evidence that some of these blocks may in fact be disrupted banding of the type occurring South of the road. In this outcrop two 'blocks' of porphyritic facies occur surrounded by glomero-anorthosite: traced across 10 metres of covered ground similar porphyritic facies rocks are seen to be part of a banded sequence. Such disruption presumably occurred prior to complete consolidation since there is no evidence of solid-state dislocation.

III. Green Feldspar Facies

As shown on Map I, this facies is restricted to a narrow zone along the core of the anorthosite, but several isolated occurrences, no larger than outcrop size, also occur; specimens 23 and 27[1], for example, occur in this way. The diagnostic field characteristic of this facies is the greeny-grey to browny-yellow colour of the feldspars which contrasts with the predominantly light bluey-grey feldspars outside this facies. It is important to stress that this is the only property readily observed in the field that is unique to this facies. In the majority of other macroscopic features rocks of this facies are identical to typical Whitestone anorthosite rocks.

For example:-

1) Both glomeropoikilitic and porphyritic green-feldspar rocks occur,

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[1] See Map 2a, in back pocket, for localities.

and they are in all respects, except colour, identical to their equivalents outside the green feldspar zone.

2) There is no difference in grain-size between green feldspar and other rocks. In typical glomero-anorthosite, for example, grain size averages 2-3 mm. with occasional darker grains up to 20 mm.; exactly the same distribution holds in the green feldspar facies.

3) It will be demonstrated below that in the body as a whole, rocks of the centre are less mafic than those on the margins; this rule is not violated by the green feldspar rocks.

4) It will also be shown in later sections that plagioclase textures and bulk chemical composition in this facies are in harmony with trends in the anorthosite as a whole.

5) Field observations show that there is a gradation from typical light-grey anorthosite to the green feldspar variety and that this gradation continues into the facies, so that rocks in the centre of the zone have a more pronounced colour than those at the edges of the facies.

In fact, it is here proposed that similarities in overall field appearance (and in many petrographic features) are so striking that there is no reason to assume that the green feldspar facies is other than normal Whitestone anorthosite that has somehow contracted green feldspars and, therefore, the problem of why the feldspars are green can be discussed separately from the origin of the anorthosite as a whole. To improve the development of the argument of this thesis it is necessary to broach the discussion of this origin now; to do this certain petrographic details are required.

Thin section examination of the green feldspar facies rocks shows narrow, randomly orientated, yellowish or brownish veins ramifying through and around the plagioclase grains. Such a feature is characteristic of the charnockites of the Madras area (Howie 1955, 1958 & 1963) and Howie considers these veins to be the cause of the puzzling dark olive-brown colour typical of charnockites s.s.. Howie (1958) demonstrated that these veins and the dark colour of the charnockites can be simultaneously removed by leaching with warm HCl, and shows that the major loss in the bleached rock is in total iron (Howie 1963): the identity of the vein mineral remains problematical. Slices of anorthosite No. 145 and 196 in warm, 5% H_2SO_4 show an identical transmogrification, in these cases from yellow-green feldspar anorthosites to white- and bluey-grey feldspar rocks which are unquestionably typical Whitestone glomero-anorthosites.

Furthermore, it is appropriate to introduce here two more trade marks of the green feldspar facies, both of which are considered genetically important.

1) It has been noted above that clinopyroxene is the dominant pyroxene phase in all facies of the anorthosite. While still being the main pyroxene phase, the clinopyroxene in this facies, and in this facies alone, displays a rim of pleochroic orthopyroxene.

2) As indicated on Map I, garnet is typically restricted to the marginal, foliated rocks. However, on occasion it also occurs in non-foliated rocks and, specifically, it invariably occurs in

the completely unfoliated green feldspar rocks where it rims the mafic minerals in an unusual corona-type texture. Where well developed this corona texture is composed of a solid chain of small, subhedral to euhedral garnet crystals, with a narrow rim of plagioclase between the mafics and the garnet. This texture is unique to the green feldspar facies.

The perfect correlation in this facies of these three characters - viz. the colour of the feldspars, orthopyroxene rims and garnet coronas - and their complete absence, both as a trinity and separately, from all other facies suggests the hypothesis that they have a cogenetic origin. Furthermore, the topological nature of these features (for example, veins in the plagioclase, rims and coronas on the clinopyroxene) all imply a secondary or late-stage process responsible for their presence. This is borne out by the sameness of all the other physical attributes of the rocks, and is consistent with the gradational contact of this facies with other facies.

That is, it is suggested that the origin of this facies is to be sought in a late stage or secondary process which resulted in the imposition of these three trademarks on pre-existing, typical Whitestone anorthosite rocks.

IV. Foliated Epidote- and Garnet- Bearing Facies

Because of many similarities it is convenient to treat these two facies together.

Their general distribution is clear from Map I and this distribution, which is based on the field recognition of garnet and/or epidote plus foliation, can be compared with Figs.5-10 & 11 (pp.176 &177) which are a synthesis of the modal analyses of some 360 thin sections distributed as in Map 2a.

The Foliation

Traced towards the margin from typical glomero-anorthosite the foliation develops by the gradual elongation and coalescence of the glomerules into discontinuous bands and streaks and, on the west at least, eventually gives rise to a thorough-going, typomorphic gneiss, as illustrated in Plates 2-12 and -13.

Concomitant with the development of the foliation two other features are noted:-

1) Change in colour of feldspar.
2) Development of epidote and/or garnet.

In the central part of the body a fresh surface of the anorthosite is composed of medium to coarse grains of various lighter and darker shades of bluey-grey with occasional coarse grains (up to 50 mm) a definite purple or purply-brown. With but rare local exceptions, garnet and epidote are absent in such rocks.

However, as the foliation develops and reaches such a stage that its attitude can be defined, the feldspars become uniformly milky-white and finer grained, and garnet/epidote appears, generally as crude coronas on the mafic minerals. Such a combination of criteria define the foliated facies.

Concerning the foliation, the following points can be made:-

1) Even in large, perfectly exposed outcrops close inspection fails to reveal any sign of minor folds; these are legion in all varieties of the envelope rocks.

2) No lineation is obvious in the plane of the foliation. While this may be the result of grain size, it is significant to note that observations on partially flattened glomerophenocrysts indicate an actual lack of orientation within the foliation plane. (See page 37)

3) In the plumper part of the pluton (i.e. N. of Shawnaga Lake) the foliation is more strongly developed on the west than on the east.

On the west, for example, the typical border rock strongly resembles, in gross features, a light grey paragneiss with bands of fine- to medium-grained pure feldspar, 2–5 mm thick, alternating with bands of feldspar plus mafics, 5–10 mm thick. The colour index of the latter bands vary slightly from band to band. No reputable evidence of a previous texture remains.

On the east, however, the foliation never becomes so pronounced, rarely passing the stage of incomplete inosculation of flattened glomerophenocrysts, and, in most cases with sufficient mafics, relics of a glomeropoikilitic texture can be confidently identified. Compare Plates 2-13 and 2-14.

Traced northwards from Snakeskin Lake the strongly foliated western type becomes more and more restricted towards the contact and in the region of the Whitestone River the bulk of the foliated rocks are of the eastern type. Towards the south the western type becomes more and more dominant, finally comprising the whole width of the anorthosite outcrop in the tail.

It is significant to note two features correlated with this

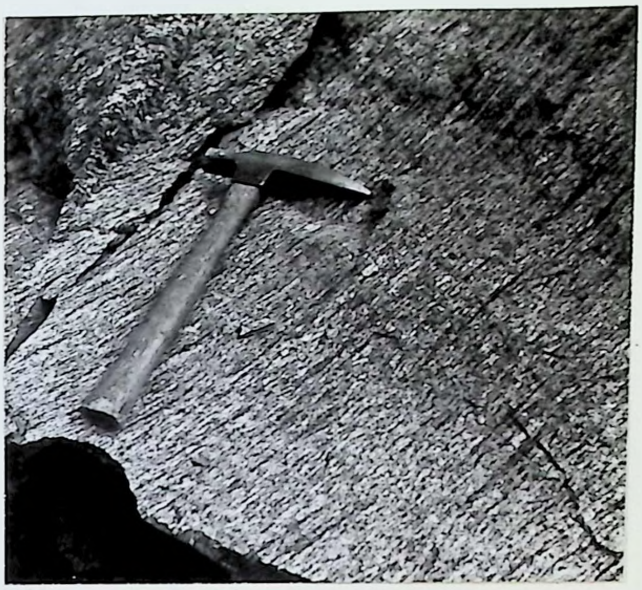

Plate 2-13 Strongly foliated anorthosite typical of western margin. No remnant of original texture. Locality at point where western gravel road crosses railroad.

Plate 2-14 Much less pronounced foliation typical of the eastern margin. Distinct glomerophenocrysts can still be discerned. N. of Grassy Bay (i.e. S.W. arm of Whitestone Lake).

contrast in development of foliation.

i) The dip of the foliation is steeper on the west than on the east (of the order of 60°-70° and 0-30° respectively) and there is reason to suspect that dips on the west may be overturned in places with respect to those on the east, which would accentuate this disparity.

ii) Of the index minerals, epidote predominates in the steeply-dipping, well-foliated western rocks while garnet predominates in the gently-dipping, moderately foliated eastern rocks.

The Testimony of Epidote and Garnet

A remarkable feature of Map I is the asymmetric and distinct distribution of the index minerals of the two foliated facies. As might be expected, detailed and microscopic examination reveals this bipartite scheme is not as exclusive as indicated, yet it will become apparent that the recognition of the two facies is a significant petrogenetic feature.

In the gneissic anorthosite of the tail and the western margin epidote can, with diligence, be recognised as a narrow, pale greenish-yellow rim on the dark minerals. The corona texture is remarkable in hand specimen and even more so in thin section. In these rocks epidote is the dominant of the two index minerals but thin, localised seams one crystal thick (0.5-1 mm) in which red garnet is common may be present in many hand specimens, although never more than to make up trace amounts in the bulk rock. In such cases, microscopic examination invariably reveals that garnet occurs only in those seams which are notably enriched in opaque minerals, the garnet usually rimming both these opaques and the ubiquitous pyroxenes. Now, it should be understood that in these western rocks oxides are, on the whole, very sparse, a thin section often containing only a solitary, small granule, but occasionally a certain narrow band or seam will be unusually rich in oxides, and it is in such bands alone that garnet occurs. In all adjacent bands the pyroxenes are rimmed by epidote. This rapport of garnet and oxide minerals turns up again and again in thin sections both of the anorthosite and the country rock; but it is the common occurrence of epidote both in the same rock and in the same paragenetic relation except for the (local) impoverishment in oxides, that emphasises the relation of garnet and oxides.

The results of copious field and petrographic observations on this facet can be summarised in the following statements:-.

1) Epidote is strongly associated with foliated rocks and is most common in rocks, or domains of rock, free of oxide minerals. It is not, however, severely restricted to such rocks: e.g. in a few isolated cases epidote has actually been observed rimming oxides (however, garnet is more abundant in these rare rocks).

2) Garnet invariably occurs in rocks containing oxide minerals but, while in some cases actually rimming the oxides, intimacy is not overly marked, and, while most abundant in foliated rocks, is not restricted to them: e.g. garnet (with oxide and Fe-rich vein material) is present in the unfoliated Green Feldspar facies rocks and in other massive, but oxide-bearing rocks (see below). Sphene is usually associated with oxides and garnet especially in the foliated rocks.

Such evidence warrants the hypothesis that in these anorthositic rocks at least, the development of garnet is a function of the local bulk composition of the rock; the activity of iron being of prime importance with conditions favouring development of foliation being only of secondary importance. In other words, the distribution of the garnet- and epidote-bearing facies are directly due to the distribution of the oxides. The main oxide phases are hemo-ilmenite and magnetite[1]. Iron is inferred to be the major significant component since titanium is only a minor constituent of the garnet (see analysis in Table 5-9); the excess titanium is presumably accommodated in the sphene which occurs as a constant accessory in such rocks. Although conceivably the garnet/epidote dichotomy could be an effect of a variable P_{H_2O} the presence of garnet + oxide and epidote alone, in bands only millimetres apart, argues strongly against this: similarly, the epidote bearing rocks do not have a significantly higher amphibole/pyroxene ratio.

In areas where the two facies are juxtaposed, as around Lac du Bois and west of Lorimer Lake, the junction is gradational in that bands of garnet-facies appear in epidote-facies rock, become abundant and, finally, dominant. This is taken to indicate the original oxide distribution.

Intriguing is the fact that everywhere on the western contact that the actual contact is exposed, garnet facies rock, with no epidote,

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[1] Kretschmar (1967) Unpublished M.Sc. thesis. See Chapter 5.

comprises the immediate contact for a distance of 10'-20' being succeeded inward by typical epidote facies rock. Rock No. 206 is such a rock. (See Table 6-1).

Further evidence both of the rapprochement of garnet and oxides, and of the distribution and origin of the oxides is abundant in the garnet facies itself. E.g.

1) Of some 360 sections for which modal data are available (Table B-1, Appendix) only 4 contain more than 0.5% opaques without also containing garnet, a fact entirely consistent with the suggested relationship. It is also significant to note that only 11 modes, including the above 4, fall outside the area defined as Foliated Garnet Facies. C.f. Map I and fig.5-10. Outside this zone the overwhelming majority of rocks have modal oxides in trace[1] amounts only, most having less than 0.1%. That is, rocks within the garnet facies on the average have more than 10 times the modal oxides of the rest of the body.
2) Within the outcrop of garnet facies local oxide concentrations are relatively common. Plates 2-15 and 2-16 illustrate typical occurrences. Features common to these "showings" are:-
    a) Invariably constituted of scattered, coarse (1-2") crystals of clinopyroxene/hornblende and oxides, corona-garnet being associated with both, set in an anorthositic matrix

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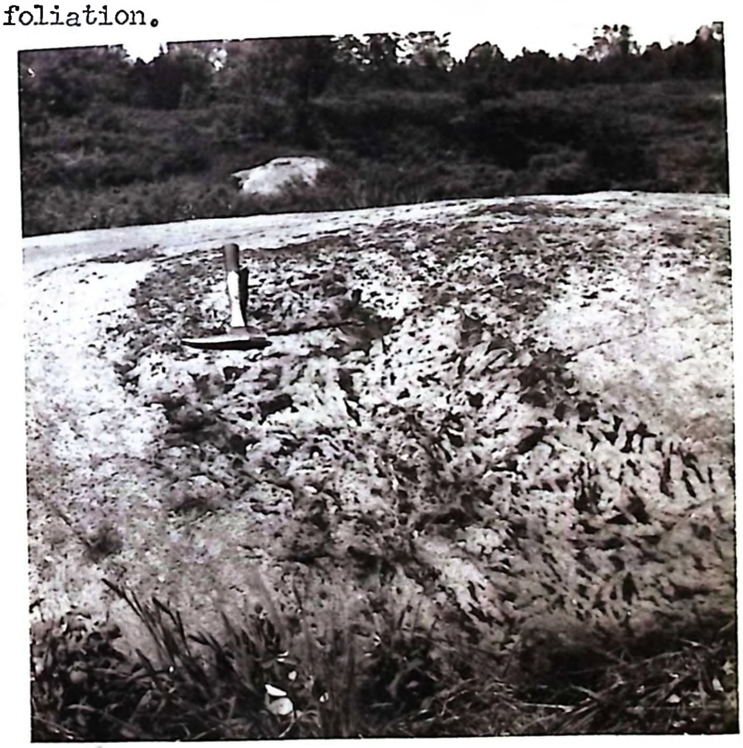
[1] Trace amount defined as less than 0.25 modal %.

<u>Plate 2-15</u> Typical concentration of coarse oxides and mafics with corona garnet. Note nebulous margins to 'showing'. Although garnet is abundant in both 2-15 and 16 there is no evidence of any foliation.



<u>Plate 2-16</u> In this (rare) situation there appears to be some control on development of oxide and mafics. Note both these are much coarser than in surrounding rock although feldspar is constant throughout suggesting oxide and mafic originate from a later, more fluid phase.

identical to the prevailing local type (e.g. in grain-size, texture and composition of the plagioclase).

b) Showings are apparently blind - i.e. no evidence of conduit through which material might have been introduced.

c) Apatite occurs only in trace amounts - contrasting with the nelsonite and similar dikes of other anorthosites and alkaline complexes.

d) Oxides mainly hemo-ilmenite and magnetite. Occur as very coarse crystals but apparently never in abundance enough to constitute an ore. A study of the oxides from a selection of such showings was carried out by U. Kretschmar (1968).

3) Within the foliated garnet facies rocks themselves oxides also occur as occasional short seams, 5-10cm. long by 0.5cm. wide, consisting of coarse oxide crystals contrasting with the general fine to medium grain of the other rock forming minerals.

4) Also in this facies irregular shaped inclusions are converted to a rusty weathering, dense, fine grained oxide- and garnet-rich rock, similar in all respects to the metasomatised gneisses which form a skin to the garnet-bearing part of the anorthosite (see next chapter). Plate 2-17 illustrates some small inclusions. These inclusions are quite variable in modal composition excepting that they are invariably rich in garnet and oxides[1]. Quartzite inclusions, which are common in the north and northwestern part

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[1] Relation is to some extent antipathetic in that if there is rock exceptionally rich in garnet it may be poor in oxides.

Plate 2-17 Inclusion in garnet facies anorthosite. N. shore of Lost Bay, Whitestone Lake.

The red colour is due partly to the rusty weathering and partly to the abundance of fine-grained red garnet. Inclusion is identical to metasomatised amphibolite of the contact aureole.

of the pluton, are not, however, affected by this apparent metasomatism.

Such field evidence is consistent with the existence of a ferriferous liquid, probably high in volatiles, which existed towards the end of the crystallisation of the anorthosite and which collected and crystallised in local pockets and within the foliation in the nearly solid anorthosite to give rise to the 'showings' and the coarse oxide seams, and, in general, contributed to the overall oxide enrichment of the garnet facies rocks. At the same time inclusions in the anorthosite were soaked and metasomatised by this fluid phase, as were the country gneisses directly juxtaposed to the garnet facies rocks (see following chapter). Such a liquid, or an evolutionary related one, could also be responsible for the singularities of the green feldspar facies.

Although none of the 'showings' discussed above attain the stature of an ore it is significant to note that current conventional wisdom ascribes the origin of the massive magnetite and ilmenite deposits associated with anorthosites to a Fe-Ti-volatile-rich magmatic liquid (e.g. Labrieville-Anderson 1966, Allard Lake - Hargraves 1962, Morin - Philpotts 1966, other references in Philpotts 1967). In fact it would appear that this is one of the few theories concerning anorthosites about which there is general agreement. Moreover, in these cases there is varied and abundant field evidence which apparently can only be rationalised on the basis of a theory involving liquid immiscibility. That is, the ferriferous liquid separated from the parental silicate magma while the latter was still partly liquid, rather than the Fe-liquid originating as an extreme residual liquid of strong fractional crystallisation of the silicate magma. Philpotts (1967) has published some exploratory experimental work consistent with this theory, indicating that a eutectic mixture of magnetite and fluorapatite (2/1) forms an immiscible liquid with a dioritic melt.

CHAPTER 3

THE FIELD GEOLOGY OF THE ENVELOPE ROCKS

3a. Introduction

As indicated in Chapter I one of the more contentious issues concerning the origin of anorthosites involves the relation of the anorthositic unit to its contiguous rocks especially when these are igneous (or supposed to be igneous). The Whitestone anorthosite itself, as shown in Map I, is nowhere in direct contact with any rock that could be construed as plutonic. Nevertheless, the relations exposed here may be, for this reason, valuable in the interpretation of controversial contacts insofar as certain phenomena found in the envelope of this body can be reasonably inferred to be due to the intrusion of the anorthosite into older rocks. Therefore, the presence of equivalent features in cases involving two igneous rocks may, cautiously, be similarly interpreted. Such an argument by analogy will be particularly potent if the phenomena can be rationalised on the basis of a reasonable physico-chemical model which can be expected to hold in the majority of cases.

3b. Regional Geology

In this chapter evidence will be presented which will support the theses that:-

a) The anorthosite was intruded into rocks <u>already metamorphosed</u> to upper almandine amphibolite facies.

b) The anorthosite imposed on the rocks both a thermal and a metasomatic aureole.

c) There has been no significant, or at best only mild, metamorphism affecting the region since the intrusion of the anorthosite.

As far as can be gleaned from the available literature (Satterly 1942 & 1954 and Lacy 1960) and from brief safaris into the largely unmapped hinterlands the rocks as described hereunder are not atypical of the general region. See Table 4-1.

For convenience the country rocks have been divided into two formations[1], the Lac du Bois and the Whitestone Lake, whose local distribution are shown on Map I. These lakes give an accessible, well exposed section of a typical development[2] of each formation - hence the names. These formations are probably equivalent to the Paragneiss-Amphibolite Group and Crystalline Limestone Group, respectively, described by Satterly in Lount Township (Satterly 1955). The boundary between them is to some extent arbitrary and subjective being drawn both on overall lithologic features and, more specifically, on the presence of abundant marble bands in the Whitestone Lake Formation; note that abundant is the operative word since occasional bands of marble occur in otherwise typical Lac Du Bois Formation rocks in the region of Shawanaga Lake. No evidence was unearthed which indicated relative ages for the two formations and the structural data, such as it is, is consistent with the two units being conformable.

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[1] An informal rock-stratigraphic unit distinguished and delimited on a lithologic basis (American Commission on Stratigraphic Nomenclature 1961).

[2] But not <u>the</u> type section.

3b(i) Lac du Bois Formation

The essential lithologies of this formation are laid out in Table 3-1, while Fig. 3-1 gives a detailed map of a typical section from Lac du Bois.

Table 3-1 Lithologies of Lac du Bois Formation

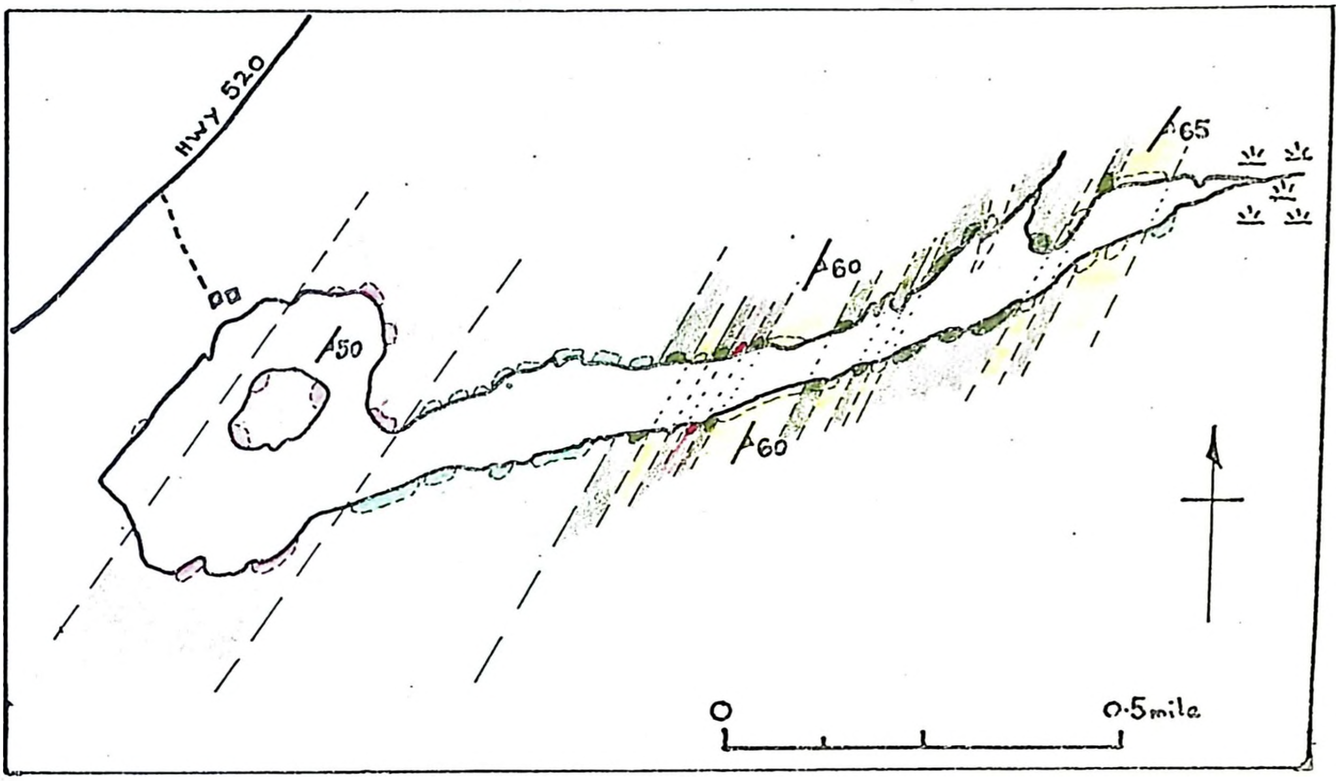
Common in this formation in area mapped	Amphibolite ± Garnet Migmatitic Biotite-paragneiss ± Garnet
Rare in this formation in area mapped	Banded unit with amphibolite and biotite paragneiss alternating on scale of a few feet Quartzite Granitic gneiss
Very rare in this formation in area mapped	Marble

A characteristic feature of the formation in this area is the rapid alternation of amphibolite and migmatite. Only rarely are individual units greater than a few hundred feet thick, a feature well illustrated in fig. 3-1, and it is this rapid repetition that makes subdivision of the formation unwarranted.

Amphibolites

Plates 3-1 and 3-2 illustrate typical developments of the amphibolites of this formation, and demonstrate the complex structure (undefined in this report) associated with these rocks.

The amphibolites, on the scale of an outcrop, form a relatively



☐ Granitic gneiss; inclusions of amphibolite common, probably a sill.

☐ Banded amphibolite & biotite-gneiss;

🟩 Amphibolite;

🟨 Qtz-felspar-biotite ± garnet migmatitic gneiss

🟥 Pink granitic gneiss, no inclusions:

Fig. 3-1. Geological Sketch Map of Western Lac du Bois.

Plate 3-1 Outcrop of typical amphibolite of the Lac du Bois formation, S. shore of Lac du Bois. Note well developed, complex, small-scale folding.

Plate 3-2 Garnetiferous amphibolite, Lac du Bois. Note banding and compare with coronite amphibolite Plate 3-7.

homogeneous lithologic unit in the field, with the following characteristics:-

1) Felsic/mafic ratio averages 0.7 with an essential paragenesis of amphibole, plagioclase ± garnet.
2) Rocks are banded to a lesser or greater degree with bands being manifested by slight variation in the felsic/mafic ratio and by veins of feldspar.
3) Despite this banding the rocks are relatively massive (with respect to fissility) and only very rarely are the amphiboles oriented to define a measureable lineation.
4) Fine to medium grained.
5) Garnet, in general, restricted to medium grained rocks, being absent or widely scattered in fine grained amphibolites.
6) Pegmatitic veins, with very coarse crystals (≃1") of hornblende, plagioclase and garnet, are present in most outcrops.
7) Traced towards the anorthosite the garnetiferous amphibolites gradually develop a striking rim of plagioclase round the garnet crystals to define a coronite amphibolite (see below).
8) Clinopyroxene and orthopyroxene are also restricted to amphibolites adjacent to the anorthosite.

Migmatitic Biotite Paragneiss

This rock type, which alternates regularly with the amphibolites, is composed of a lighter to darker grey biotite-feldspar-quartz gneiss fraction (melanosome) and a pink quartzo-feldspathic fraction (leucosome) as illustrated in plate 3-3. Characteristics of this unit are:-

Plate 3-3 Migmatite on Hwy. 520 near Whitestone village.

Plate 3-4 Ptygmatic migmatite on western end of Lac du Bois.
Note mafic enriched sheath to the granitic fraction of rock.
Black dots are garnet crystals, occurring in both granitic and paragneiss fractions.

1) Main variable is ratio biotite/qtz.-felds. in melanosome.
2) Melanosome fine to medium grained and gneissic banding well developed.
3) Leucosome sensibly coarser (occasionally almost pegmatitic) than melanosome.
4) Leucosome may be fairly regular as in Plate 3-3 or ptygmatically contorted as in Plate 3-4.
5) Red garnet porphyroblasts developed in some (favourable?) migmatites, not obviously related to anorthosite or other plutonic intrusions. Plate 3-4.
6) Within several tens of yards of anorthosite this unit is completely recrystallised and, while banding and differentiation of melanosome and leucosome is retained, there is overall decrease in grain-size, the grain-size difference between melanosome and leucosome is annuled, and the rock becomes highly speckled with abundant, small, subhedral, blood-red garnets. In most cases clinopyroxene is developed in these contact rocks.

The observations noted above coupled with 7) and 8) under amphibolites, point to an *extra*, contact metamorphism of the rocks near the anorthosite indicating a relatively high temperature of intrusion for the anorthosite. However, more significantly, these points also demonstrate that these country rocks were *already metamorphosed* to a high grade before the intrusion of the anorthosite, and, since these typical contact metamorphic phenomena are still blatantly extant, it appears that the area has been subjected to little, if any, *regional* metamorphism since the intrusion of the anorthosite. That is, it seems unreasonable that a regional metamorphism of a grade sufficient to recrystallise, foliate and develop epidote and garnet in the immediately adjacent anorthosite would leave this aureole in its pristine condition.

This point, having been introduced here, will be returned to later.

Banded Amphibolite and Biotite Gneiss

This unit, figured in Plate 3-5 and located on Fig. 3-1, is similar in its separate parts to the amphibolites and gneiss described above with the following qualifications:-

1) Amphibolite horizons are usually fine grained and rarely contain garnet.
2) Biotite gneiss horizons are rarely migmatitic.

As illustrated in Plate 3-5 the rock is banded on a scale of several inches to several feet. Although not differentiated on Map I it can be traced both S. and N. remaining sensibly concordant with the granitic gneiss unit.

Granitic Gneiss

On Map I the outcrop of a fine to medium grained, relatively massive, pink granitic gneiss is delineated. This granitic gneiss is cut by a hornblende-bearing pegmatite and apparently this pegmatite follows the outcrop of the granitic gneiss fairly closely. Irregular inclusions of amphibolitic material suggest that this unit is a sill.

This granitic gneiss, being a rare lithology in this area and also being easily recognised, was mapped separately only to indicate regional structure.

Plate 3-5 Banded unit consisting of narrow, alternating bands of amphibolite and biotite paragneiss.
Western end of Lac du Bois.

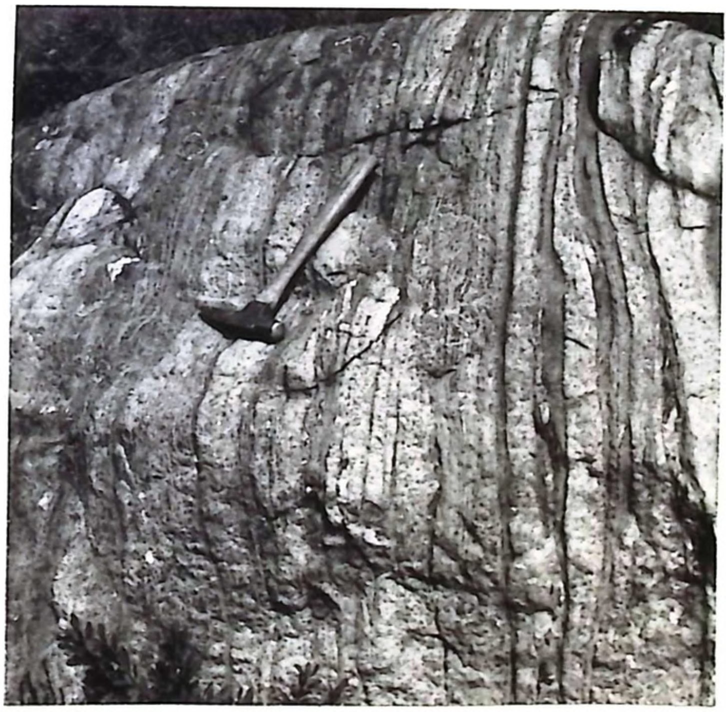


Plate 3-6 Thinly bedded orthoquartzite. Lac du Bois.

Quartzite

A minor unit of the Lac du Bois formation is the glassy orthoquartzite present as a narrow band some 50-60' thick on Lac du Bois but which appears to thicken considerably at the N.W. of the Whitestone body, as shown on Map I. The reason, tectonic or otherwise, for this local thickening remains obscure.

The quartzite itself is usually well bedded (Plate 3-5) and apart from medium grained quartz, only minor amounts of feldspar are visible.

Narrow bands, or lenses, of quartzite are found interbanded with the metasomatised gneiss to the N.E. and E. of the anorthosite, and quartzite rafts are also found in the extreme north within the anorthosite.

Coronite Amphibolite

Only the field evidence of this rare and interesting rock type is discussed in this section.

The singular texture of this amphibolite is illustrated in Plate 3-7 and its distribution shown on Map I.

In essence the rock is a garnetiferous amphibolite in which each separate garnet crystal is completely rimmed by white feldspar to give the rock a bird's eye texture. In such features as variation in mafic ratio from band to band the rock is a typical amphibolite.

In both hand specimen and thin section a reciprocal relation between the amount of garnet and plagioclase is observed: i.e. where the plagioclase rim is thick the garnet core is small, the total corona remaining essentially constant in size. This observation favours the conclusion that the garnet is in the process of breaking down to plagioclase (+ clinopyroxene, see chapter 4 and compare Plates 4-2 and 4-3).

Plate 3-7 Coronite amphibolite, Lac du Bois.
Note similarities in gross features to Plates 3-1 and 2.

Evidence that such a reaction is due to the intrusion of the anorthosite (i.e. a further facet of the contact aureole) includes the following:-

1) The texture is observed only in amphibolites less than 400 yds. from the edge of the anorthosite[1].

2) On the other hand, except for a small area on Shawanaga Lake (due S. of Duval Lake), no non-coronite (i.e. normal) garnetiferous amphibolite occurs within $\frac{1}{4}$ mile of the anorthosite. Note presence of coronite on S. shore of Shawanaga Lake, on N. Whitestone Lake and area due N. of anorthosite.

3) On Snakeskin, du Bois and Taylor Lakes amphibolites further from the anorthosite than $\frac{1}{4}$ mile show evidence of incipient development of feldspar rims on the garnets over a distance of $\frac{1}{4}$-$\frac{1}{2}$ mile from the well developed coronite amphibolite.

These points taken together indicate that, rather than being due to, say, the special chemistry of a particular horizon of amphibolite,

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[1] In case of coronite exposed in area north of anorthosite and extending towards the Magnetawan River, independent evidence suggests that the anorthosite dips or plunges under the cover in this direction.

the coronite texture is a property of amphibolites which outcrop within $\frac{1}{4}$ mile of the anorthosite.

3b(ii) Whitestone Lake Formation

Typical lithologies of this formation in the area studied include marble, quartz-poor hornblende plagioclase gneiss and biotite-quartz-plagioclase gneiss: in contrast to the Lac du Bois formation it is negatively typified by a lack of migmatites and general poverty of amphibolites. As stated above, the boundary between the two is apparently transitional[1] and therefore arbitrary. In general, however, marble associated with hornblende-plagioclase gneiss etc. was mapped as Whitestone while marble associated with migmatites and amphibolites was mapped as Lac du Bois. Defined thus the majority of marble outcrops in the Whitestone Lake formation.

Probably as a result of the abundance of marble this formation is poorly exposed compared to the Lac du Bois.

Marble

The features of the marble in this area have been discussed by both Satterly (1942 & 1954) and Lacy (1960). Essentially the marble is composed of a non-oriented, interlocking mosaic of very white and very coarse calcite; (grains 5-10 mm. are abundant). This pure marble serves as a matrix in which floats remnants of thin seams of amphibolitic and silicious, impure carbonate material. These inclusions occur either as complexly folded, completely disoriented remnants or as angular nodules

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[1] In all probability the actual boundary is tectonically modified.

and blocks, and often constitute enough of the total rock to justify the term marble breccia. See Plate 3-8 and 3-9.

Although no special study was made several cases of inclusions showing tight folding in two directions were found which would seem to bespeak a complex tectonic history for the country rocks of the area.

As noted by Lacy the outcrop of the marble together with the regional E.N.E. joints have influenced the shape and probably the position of Whitestone Lake. Reefs and shallows on the main part of the lake are generally marble and, moreover, on the E/W arms many of the bays and gulleys are set in marble bands. Due to poor exposure it is not possible to correlate the marble from exposure to exposure nor to accurately assess the amount of marble. Actual marble exposures are shown on Map I.

Hornblende Plagioclase Gneiss

This rock type occurs interbedded with the marble mainly in the area between the anorthosite and the diorite.

It is a medium-grained, very strongly foliated gneiss, poor in quartz and with a hornblende/plagioclase ratio of approximately 0.2 (i.e. less than $\frac{2}{3}$ of an amphibolite). Interbanded conformably with this gneiss are narrow bands, of 1'-2' thick, of pink granitic rock; these are common enough to virtually form a diagnostic feature of the lithology.

Biotite Gneiss

This unit occurs interbedded with marble mainly in the area east of the diorite. It is differentiated from the Lac du Bois gneiss in being non-migmatitic, coarser grained, more strongly foliated yet more homogeneous (i.e. gneissic banding poorly developed). It occurs in both pink, grey and white varieties depending on percentages of potassium

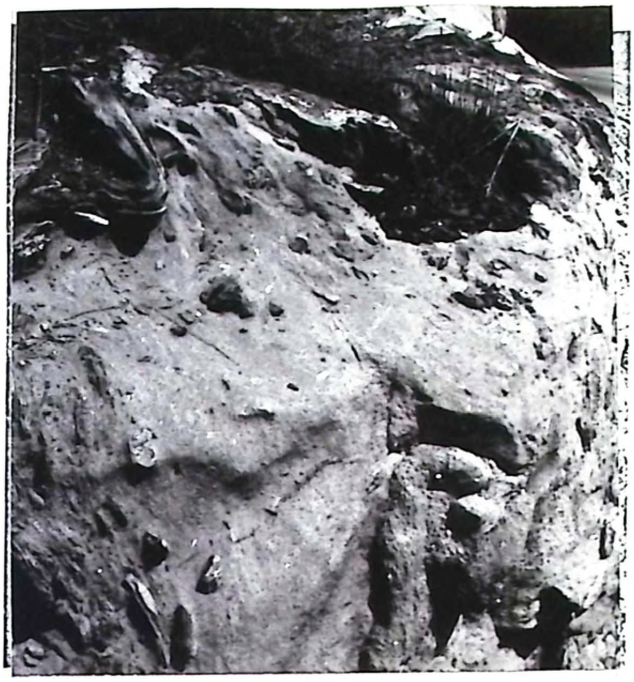

Plate 3-8 Coarse grained marble breccia. Hwy. 124 near Fairholme. Note many of fragments show evidence of folding prior to brecciation.

Plate 3-9 Coarse grained marble with disconnected, folded beds of amphibolite (para?).
Small island in S.E. Whitestone Lake, south of narrows.

feldspar and biotite. Essential minerals are quartz, feldspar and biotite in that order.

3b(iii) Metasomatised Gneiss

In Chapter 2 the subdivision of the country rocks of this area proposed by Lacy was briefly given (2a(ii) p.30) and it will be noted that in the present chapter the liberty of amending this classification has been taken. This has been done mainly for the reason that part of the definition of his Whitestone Lake Metasediments involves a unit of "rusty-weathering gneisses" which, it is here proposed, are in fact a heterogeneous group of pre-existing lithologies which have all been subjected to a metasomatism emanating from the anorthosite and which thereby have had imposed on them a certain, ostensibly unifying aspect.

Suggesting consanguinity for these gneisses are the field observations that all are rusty-weathering, unusually rich in both modal oxides and garnet, as well as being generally dense and fine-grained. On the other hand, evidence indicating that such features are not protolithic in origin are the facts:-

1) Distribution of the "lithology" is restricted to rocks juxtaposed to the garnet-bearing foliated facies of the anorthosite. (It will be recalled that the garnet-bearing facies contains evidence of an iron-rich fluid.) Distribution is illustrated on Map I as area between anorthosite and dotted line marked "Limit of Metasomatism observed in field".
2) Examination of separate outcrops reveals that the diagnostic rustiness etc. exists in rocks heterogeneous in mafic content

and texture. For example, some of the rocks have a very high mafic mineral content while others are much more felsic and many of these latter show typical migmatite bipartism. See Plate 3-10 and compare with much more mafic block in Plate 2-19. Table B-2 (Appendix), of modal analyses of such rocks, gives further indication of the variability of these rocks.

Philpotts (1966) considers a rock type of the Morin Series which he calls jotunite as an intermediary in the evolutionary, magmatic sequence anorthosite to mangerite. A (or the) characteristic feature of this jotunite, although not emphasised by Philpotts, is its richness in oxide minerals. Table 4 in Philpotts' paper gives modes of three jotunites and they show 15.5%, 12.5% and 16.5% oxides, values much higher than other rocks in the 'series'.

Evidence that the gneisses under discussion are not of magmatic origin is summarised in statements:-

1) These gneisses are randomly variable with respect to both composition and texture.
2) They are interbedded with recognisable bands of quartzite and marble with no obvious intrusive relations.
3) A feature of these rocks is the complex, small-scale folding, a feature completely absent from the anorthosite but abundant in typical country rock.

As indicated above these rusty gneisses are supposed to have resulted, in fact, from the metasomatic action of fluids expelled from the anorthosite which, percolating through favourable channels in the country

Plate 3-10 Metasomatised migmatite, N. shore of Lost Bay, Whitestone Lake. Note quartz-feldspathic fraction has not been affected by the metasomatism.

Plate 3-11 Metasomatised hornblende-plagioclase gneiss, Farley's side-road. Dark band beneath compass is most severely metasomatised although whole rock is rusty to some extent.

rock, chemically modified these rocks and such modification is most obviously manifested by the development of Fe-Ti-oxide minerals. The country rocks so affected are amphibolites and migmatites of the Lac du Bois, and hornblende-plagioclase gneiss of the Whitestone Lake formation.

Further discussion of this metasomatism will be deferred until petrographic and chemical evidence is presented. Nevertheless certain field observations pertinent to the mechanism of metasomatism should be noted:-

1) Metasomatism is not homogeneously developed even in the same outcrop. Occasionally, for example, schlieren or bands of relatively unaltered material[1] (i.e. non-rusty and non-garnet rich etc.) occur in typical rusty gneiss, or as is common in the hornblende-plagioclase gneiss of the Whitestone Lake formation, only certain more mafic bands will be affected by the introduction of abundant oxide minerals while the immediately adjacent bands may not be recognisably affected (see Plate 3-11).
2) Further it is noted that it is only rocks or bands already rich in ferromagnesian minerals that are severely altered. For example, Plate 3-10 illustrates that the leucosome of the original migmatite is hardly affected; similarly feldspathic bands in original amphibolites remain unscathed: also, bands of quartzite of the Lac du Bois formation in the N.W. Whitestone Lake area remain fresh orthoquartzite

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[1] These unaltered portions in appropriate cases are similar to typical amphibolites of the Lac du Bois Formation although they are now fine grained and recrystallised.

although interbedded with highly ferriferous gneiss and, perhaps most surprising, marble beds show absolutely no effect of the metasomatism. It should be noted, however, that the marble occurs generally towards the limit of metasomatism, nevertheless several cases of marble flanked by metasomatised gneiss were mapped.

Although it is not yet perfectly clear it may well be that the heterogeneity of the metasomatism may be a reflection of the differential 'porosity' of the heterogeneous country rocks under the relatively high temperature and pressure prevailing during the intrusion of the anorthosite. Now the porosity, in the sense of voids, will probably be nil or vanishingly small in all the various rock types. However, it is noted that the minerals biotite, hornblende and garnet are abundant and contiguous in such mafic-rich rocks as amphibolites and the melanosome of migmatites. but are completely absent, or widely dispersed, in such as pure marble and quartzo-feldspathic bands. It might be predicted from the physico-chemical nature of the parageneses of these hydrous minerals that they would react rapidly and vehemently to physical changes (mainly temperature) induced by the intrusion of the anorthosite. One outcome of such a tendency to chemical readjustment would be the development of a pervasive intergranular fluid phase in the mafic rocks. This fluid phase would, therefore, render those rocks containing it effectively 'porous' to an extraneous fluid phase, due to the greatly enhanced diffusion properties of fluids; rocks which did not, or could not, develop such a fluid phase would remain impermeable to a fluid emanating from the anorthosite.

3c. Some Structural Data

Unfortunately the Whitestone pluton is set in approximately 15,000 sq. miles of virtually unmapped territory and, as is clear from Map I, the present work has been concentrated on the body of anorthosite itself. Obviously this effectively emasculates any attempt at an independent, regional, structural synthesis, and in particular, militates against independent evidence of the spatial and temporal relation of the anorthosite to the episode(s). Moreover, even the data collected is indifferent since mineral lineation is very poorly developed[1]. This lack of mineral lineation may be due to the relatively coarse grain of the country rock and perhaps is also influenced by the contact aureole of the anorthosite. In the result only planar data, represented by gneissic banding and foliation, is available and this only for the anorthosite and a relatively thin skin of envelope rocks.

This data, for the northern part of the area, is conveniently summarised in Fig. 3-2 and attention is drawn to three points.

1) The diagram illustrates the difference in the dip of foliation in the anorthosite between the eastern and western margins, as noted in Chapter 2.
2) In all three sub-areas there is a distinct disparity between the plots of the anorthosite and country-rock poles to foliation.

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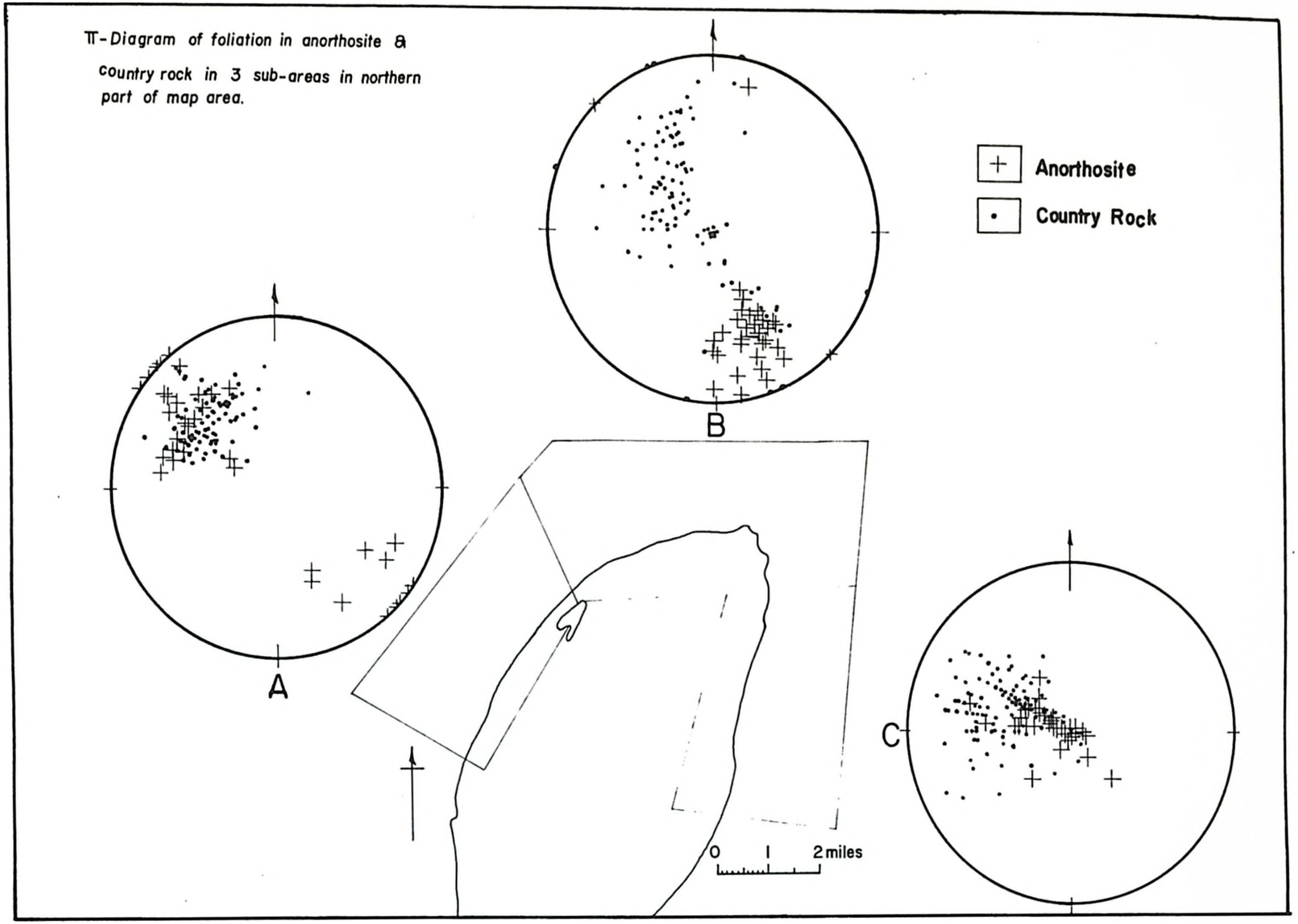
[1] This is not to say no linear fabric element exists. A suite of orientated quartz-rich gneisses were collected in the hope that petrofabrics might define linear elements but so far this avenue has not been explored further. Time considerations militated against unearthing and measuring the less accurate, and scarcer, alternatives such as minor fold axes.



π-Diagram of foliation in anorthosite & country rock in 3 sub-areas in northern part of map area.

Fig. 3-2

3) Sub-area B, at the nose of the pluton, shows the widest scatter of poles to country rock foliation. Note that much of the extra scatter (e.g. from the N.W. to S.E. quadrant of diagram B) is due to variation in dip rather than strike.

The fragmentary nature of this data restricts their significance and, therefore, it seems more appropriate to consider the structural data in conjunction with other data rather than as an independent facet.

CHAPTER 4

METAMORPHISM IN THE ENVELOPE ROCKS

4a. Preamble

Rather than an exhaustive petrographic description, the purpose of this chapter is to establish in more detail the presence and nature of the contact aureole and associated metasomatism since these obviously are of significance to the petrogenesis of the anorthosite. Logistical problems inherent in a Ph.D. thesis have curtailed the amount of time that could be devoted to this facet of the problem and it will become apparent that many of the problems which arise warrant much more careful study. In the event, particular care is taken to establish the following points as securely as possible:-

1) Regional metamorphism is of upper amphibolite facies grade.
2) The anorthosite has imposed on these, already metamorphosed, rocks a metasomatism which in essence involves the addition of Fe, Ti and volatiles.
3) Virtually simultaneously with this, the heat of the cooling anorthosite has induced a recrystallisation with concomitant phase changes so that rocks within the contact aureole are raised to granulite facies grade. The particular phase changes occurring are controlled to a large extent by the

unusual bulk chemistry imposed by the metasomatism.

4) There has been no metamorphism of any consequence since the development of the contact rocks.

In the course of establishing the validity of these points some effort is made to be more specific in respect of conditions and processes. It is possible that some, depending on their personal predilictions, prejudices and specialised knowledge, may reckon that in various instances such elaboration stretches the available data overmuch. The analytical data, in particular, is skimpy and it would be desirable to have more knowledge of

a) chemistry of representative gneisses outside the aureole
b) quantitative data on minerals from all rock types especially the country gneisses. The electron probe would be extremely useful in this regard.

While conceding this, I re-emphasise that the principal aim of this chapter is to achieve the acceptance of points 1-4 phrased as given, and, if these are borne in mind, I will argue that the tarnishing of some of the gilt will not affect the edibility of the gingerbread.

Modes relevant to this chapter are collected in Tables B-2, 3 and 4 of Appendix B. Map 2-b (in back pocket) gives localities for these samples.[1]

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[1] Note that in Map 1 all the samples collected are located as black dots, but for the sake of clarity they are not numbered on this map. However, it is hoped that it will be relatively easy to locate samples, numbered on Map 2-b, on this larger map if so desired. This also holds for anorthosite samples.

4b. Regional Metamorphism

The obvious approach to use in indicating the nature of the contact aureole is to contrast the phase and fabric features of rocks proximal to the anorthosite with their more distal equivalents. For this, and also to recognise the regional grade of metamorphism, it is necessary to consider those distal rocks which are supposed to represent the pre-anorthosite condition.

To give the reader a frame of reference it is useful to anticipate and note that adjacent to the main body of the anorthosite the contact aureole is approximately 700-800 metres wide but thins to 100-200 metres adjacent to the tail.

Quartzo-feldspathic Gneisses

Allowing for original chemical variation, represented in modal variations, the migmatites of the Lac du Bois formation are relatively homogeneous petrographically. The common assemblage of their mafic fraction is :-

Qtz-plag-K/spar-biotite ± garnet with oxides and rare, euhedral sphene. The equigranular, sutured felsic minerals serve as a matrix to well-orientated laths of greeny-brown biotite. Red garnet, while modally minor, is widespread occurring as rounded, sub-hedral porphyroblasts. The K-spar is usually untwinned but examples with indistinct, microcline twinning are also found. It is significant to note that muscovite is paragenetically absent; occurring in trace amounts only, it is invariably wholly enclosed by, or cross-cuts, the biotite. The leucosome of the migmatite, composed of qtz-plag-K/spar in roughly equal proportions, is generally sensibly coarser than the melanosome.

The biotite-gneisses of the Whitestone Lake formation have an identical mineral assemblage (excepting garnet is much rarer) but their texture is markedly different. In these rocks the dominant feature is long, narrow folia of quartz which snakes between augen of plagioclase. The augen are themselves surrounded by a fine-grained crush of feldspar. There is remarkably complete separation of quartz and feldspar into these contrasting habits.

An identical texture is found in the hornblende-plagioclase gneisses of the same formation. See Plate 4-1. In these rocks the common assemblage is

Plag-qtz-K/spar-hble-biotite ± garnet with accessory oxides.

The plagioclase is often antiperthitic and all gradations from semi-regular stringers, through irregular patches to completely exsolved K-spar can be found.

To estimate the metamorphic grade, the absence of muscovite and the co-existence of garnet and K-spar are especially noted and, as a comparison of a and b in fig. 4-1 demonstrates, these facts are consistent with these rocks being of the sillimanite-almandine-orthoclase subfacies (b) rather than the lower grade kyanite-almandine-muscovite subfacies (a). Corroborating this is the apparent transition from microcline to orthoclase observed in the migmatites (compare K apex in 4-1 a & b). This transition has been noted by Buddington (1963, 1965 p.72) in going from his zone A to the highest grade zone E in the N.W. Adirondacks. Less specific is the folia-type quartz texture of the Whitestone Lake formation; such fabrics are invariably found only in rocks of the highest grade of

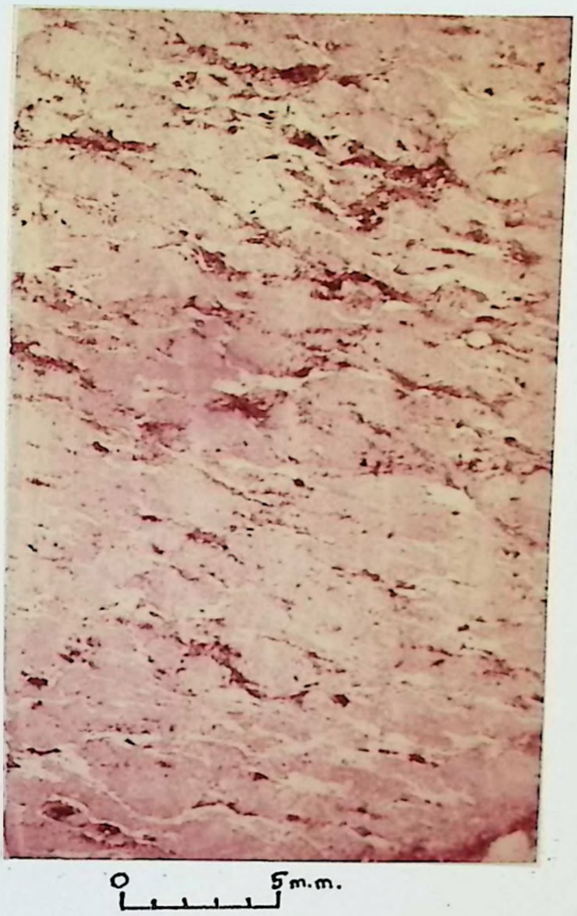
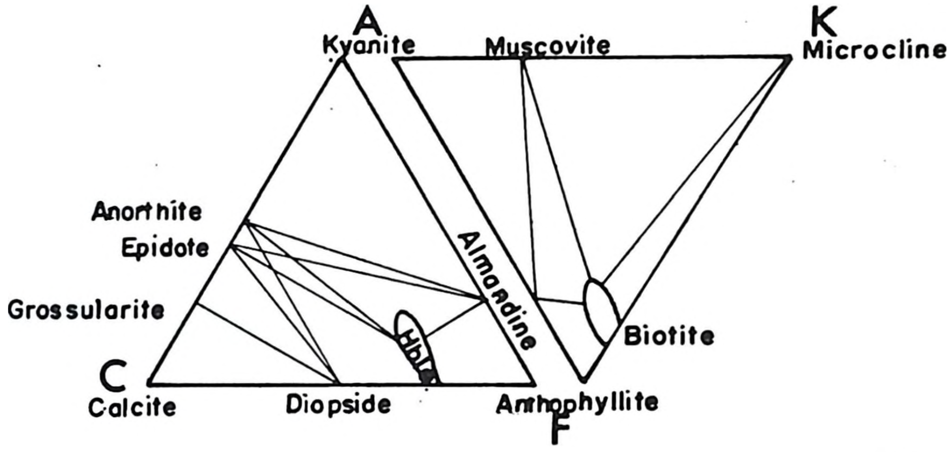
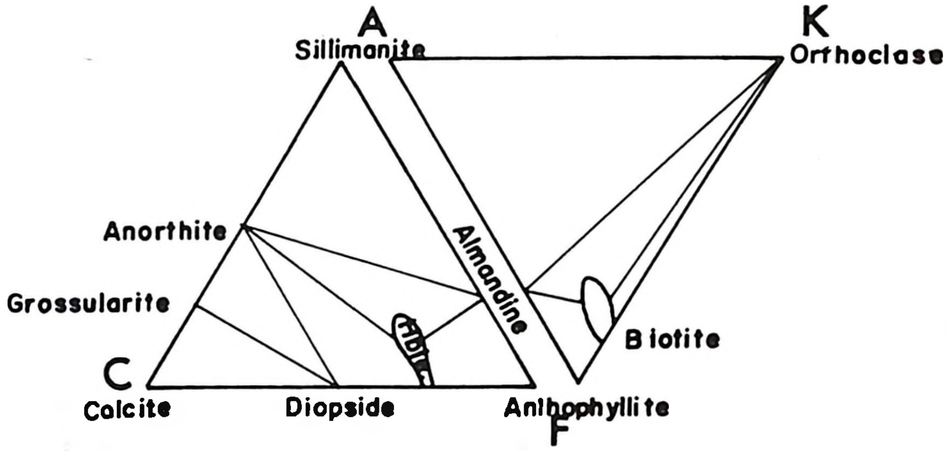


Plate 4-1 Stained hornblende-plagioclase gneiss of Whitestone Lake Formation - plane.
Qtz. - colourless
K-spar - orangy-yellow
Plag. - pink
Mafics are hornblende and biotite.
Note that quartz is restricted to narrow folia, snaking between 'augen' of plagioclase. Under crossed nicols it is seen that these augen are in fact made up of many small grains. Such a texture is not apparent in the unstained slide.



A. Kyanite - almandine - muscovite subfacies.



B. Sillimanite - almandine - orthoclase subfacies.

Fig. 4-1. Phase relations in the upper amphibolite facies.

(After Winkler 1967.)

metamorphism, usually the granulite facies (see e.g. Eskola 1952).

Even in the conservative scheme of Fyfe & Turner (1966) who question the utility of the sub-facies concept, such evidence would indicate rocks of the (upper) amphibolite facies and they would agree with Winkler (1967) on the probably prevailing conditions - temperatures around 700° C at water pressures of 4-5Kb. Anatectic melting of gneisses of appropriate composition can take place under these conditions. We note the abundance of migmatites.

Amphibolites

Amphibole and plagioclase ± garnet with trace amounts of quartz, oxide and sphene, and secondary biotite peripheral to the amphibole comprise the paragenesis of the amphibolites of this area. The complete absence of epidote and clinopyroxene in all rocks is especially noted. The amphibole itself occurs in 1-3 mm, irregular plates which are generally poorly orientated, but this varies from rock to rock. A large 2V (near 90°), maximum extinction $\hat{Zc}=18^{\circ}$ and a pleochroic scheme X=yellow-green, Y=green and Z=dark green indicates a common hornblende composition. The plagioclase is typically untwinned and strained but a few extinction measurements on suitable sections indicate a composition of An_{35}. The presence or absence of garnet in amphibolites outside the aureole is not related to distance from the anorthosite, presumably being a function of the bulk chemistry. In contrast to the coronite amphibolite the garnets in these rocks can occur wholly or partly surrounded by amphibole or plagioclase with equal frequency.

Such data are consistent with an upper amphibolite regime.

Marble

In the more silicious bands interbedded with the marble a common assemblage is garnet-amphibole-scapolite diopside and calcite. In the purer marbles well-scattered, rounded diopside and phlogopite float in a matrix of very coarse calcite. Again these assemblages are consistent with an upper amphibolite grade.

Comparison with Lount Township

Table 4-1 summarises assemblages reported by Satterly in Lount township, some 10 miles E. of the Whitestone area (see fig. 1-1). These indicate, along with brief personal safaris into the largely unmapped hinterland of the anorthosite, that the upper amphibolite facies proposed can be regarded as of regional extent.

4c. The Contact Aureole

In section 4d it will be shown that the main metasomatic effect is the addition of Fe, Ti and volatiles; in the last chapter it was noted that in the area shown on Map I this metasomatism could be easily recognised in the field on the bases of abundance of garnet and oxides and overall rusty appearance of the gneisses. While it is generally recognised that all contact aureoles involve some metasomatism, especially regarding the fugitive components, such metasomatism is conventionally disregarded unless it is particularly intense[1]. Therefore it is useful

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[1] Barth (1962) states "The heat conductivity of rocks is so low that gases and vaporous emanations become chiefly responsible for the transportation and transfer of heat into the country rock". p.262.

TABLE 4-1

Comparison of assemblages in Whitestone area and Lount township

	Whitestone Area	Lount Township
Biotite Gneisses & Migmatites	Qtz-plag-orthoclase/microcline-biotite Qtz-plag-orthoclase/microcline-garnet-biotite	Qtz-olig-microcline-orthoclase-biotite (p.14) Qtz-olig-andesine-garnet-biotite (p.10) Qtz-olig-hble-biotite (p.10)
Amphibolites	Hble-plag-(biotite) Hble-plag-garnet-(biotite)	Hble-plag-biotite Hble-plag-biotite-garnet Hble-plag-garnet Hble-plag-augite[1] Hble-plag-augite-hypersthene[1]
Amphibolites interbedded with marble	Hble-scapolite-garnet-augite	Plag-scapolite-augite-garnet Plag-scapolite-hble-augite-garnet

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[1] Satterly notes that he groups many rocks as amphibolites which are probably foliated margins of gabbroic plutons. By analogy with the diorite of the Whitestone area these particular assemblages are taken to be representative of this lithology.

in developing the argument, and not entirely arbitrary, to consider separately those rocks which clearly demonstrate the effects of metasomatism (next section, 4d) and those which show evidence of recrystallisation but lack clear evidence of metasomatism (this section), but without such classification implying a complete absence of metasomatism in the latter case.

4c(i) Coronite Amphibolite

In chapter 3 the field distribution of this remarkable rock was shown to be consistent with its origin as a contact metamorphic rock. It also lacks the obvious abundance in garnet and oxides and the rusty character of the typical metasomatised rock. However, comparison of chemical analyses in table 4-2 indicates the probability of a limited degree of metasomatism. It appears that such changes in composition have been absorbed by a change in the chemistry of the phases rather than the development of oxide phases (see below).

A Note on Coronas and Coronites

A paper by Shand (1945) remains the best survey of the morphology of coronas and coronites. He defines coronas as the reaction rims between minerals in which the reactants and/or products occur as successive sheaths or shells; the number of such shells varies - thus, a one-ply corona, a two-ply corona, etc.. He imposes the condition that such reactions be of a 'discontinuous' type (i.e. new phase(s) formed) to distinguish the process from zoning in plagioclase, for example.

Coronite, on the other hand, is a rock containing a corona texture. Thus - 'coronitic troctolite' or 'coronite amphibolite' etc..

To those who find this digression superfluous I point out that in a paper of immediate relevance Bartholomé (1960) lists in his table 2 a series of features which purports to distinguish coronitic rocks from porphyroblastic rocks: in fact, what his table does is distinguish between garnet occurring as a corona and garnet occurring as a porphyroblast - both the rock types he seeks to differentiate are in fact coronites.

TABLE 4-2

Comparison of analyses of coronite amphibolite with average amphibolites

	A	B	C	D
SiO_2	49.29	48.21	44.14	46.96
TiO_2	1.35	1.57	2.63	2.72
Al_2O_3	14.97	14.98	16.02	14.16
Fe_2O_3	2.28	3.57	1.22	3.00
FeO	8.06	8.95	13.75	12.37
MnO	0.13	0.18	0.24	0.15
MgO	5.94	6.82	7.44	6.02
CaO	9.51	9.23	10.10	10.60
Na_2O	3.50	3.49	2.68	2.94
K_2O	1.32	0.40	0.49	0.48
P_2O_5	0.21	0.15	0.54	0.14
CO_2	1.83	0.60	0.00	n.d.
H_2O	0.94	1.32	1.07	0.57
Total	99.33	99.47	100.39	100.11
Total Fe as $Fe_2O_3 + TiO_2$	12.59	15.09	19.13	19.47
$\frac{MgO \times 100}{MgO \times FeO}$	57	57	49	46

Mode of D

Qtz	-
Garnet	20%
Augite	20%
Hypersthene	2%
Hornblende	20%
Andesine	35%
Magnetite	2%
Apatite	1%
	100%

		Reference
A.	Average of 34 para-amphibolites.	van de Kamp 1968 Table XVI
B.	Average of 17 ortho-amphibolites.	" " "
C.	Coronite amphibolite No. 474 Analysis of hornblende from this rock given in Table 4-3.	This work. Analyst J. Muysson, McMaster.
D.	Amphibolite 1 mile N. of North Whitestone Lake. Presence of hypersthene and augite taken with approximate locale indicate that this rock is probably a coronite amphibolite.	Lacy (1960)

Characterising this rock type is the development of a regular corona of plagioclase on the garnet crystals and the development of pyroxene in the matrix of the rock[1]. Petrography of samples from widely scattered localities indicates the following features are of genetic significance.

1) The corona structure varies from 2-5 mm and is of similar size in all samples but the ratio plag./garnet varies widely. When the plagioclase halo is narrow the garnet is more nearly idiomorphic, although with ragged edges; where the plagioclase halo is thicker the garnet occurs as small, ragged, fragmentary grains set in a mosaic of sub-polygonal plagioclase. Compare Plate 4-2 and 4-3.
2) Inclusions in the garnets are mainly very fine-grained sphene which appear to be disposed parallel to crystal faces rather than in a helicitic fashion.
3) In general the thicker the plagioclase halo the more pyroxene occurs in the matrix (see Plate 4-2 and 4-3). In some cases a bright green clinopyroxene occurs alone, both as small interstitial grains in the matrix and larger porphyroblasts with abundant inclusions of plagioclase. (The latter type is particularly common in the vicinity of quartz veins). In other cases a pleochroic (pink to green)

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[1] For purposes of discussion it is convenient to regard the rock as composed of a corona, involving garnet and plagioclase, set in a matrix of hornblende, pyroxene and plagioclase ± quartz, oxides, sphene and apatite.

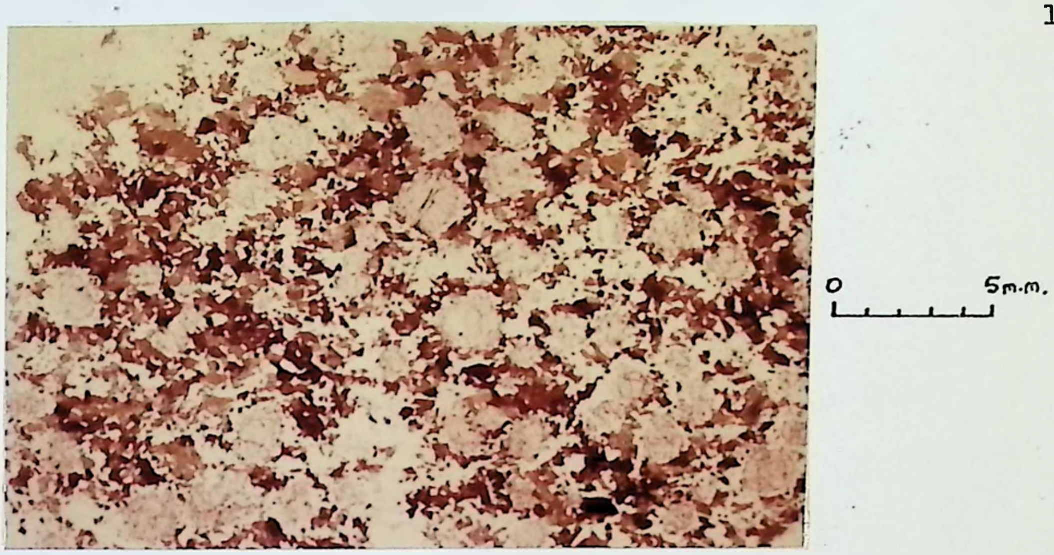

Plate 4-2 Coronite amphibolite, plane.
Note very narrow rim of plagioclase on garnets and brown colour of amphiboles.

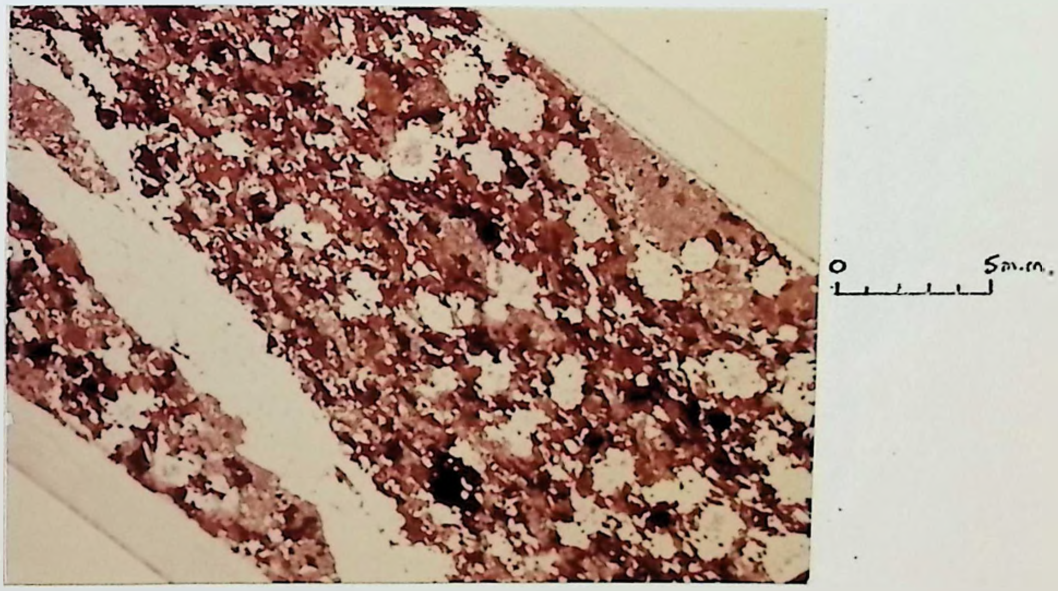

Plate 4-3 Coronite amphibolite - plane.
In this example only remnants of garnet remain in large corona of plagioclase. At same time pale green pyroxene has become much more abundant.

orthopyroxene is also developed, commonly as small interstitial grains within the matrix. It is significant to note that both pyroxenes usually occur within the matrix of the rock and are not usually spatially related to the corona.

It is not certain that it is temperature that controls the presence or absence of orthopyroxene. I see significance in the observation that the orthopyroxene invariably contains inclusions of, or is closely juxtaposed to, oxide grains; the clinopyroxene is only very rarely associated with oxides.
A myrmekitic garnet is usually associated with the oxide and orthopyroxene; the habit of this garnet is in contrast to the garnet in the corona, with the plagioclase vermicules indicating that it is growing at the expense of plagioclase and oxides. The strong modal and topological correlation of garnet and oxide in both the anorthosite and the metasomatised gneisses is recalled. Noting that there is a general rule in metamorphic rocks that the orthopyroxene is significantly richer in Fe than the coexisting clinopyroxene (O'Hara (1960), Wilson (1960), Muir & Tilley (1960)), it appears to me that very local sources rich in Fe (of the order of a few c.c.s), inspired by the local presence of an Fe-oxide phase, control the development of orthopyroxene.
I propose that because the coronite amphibolite is developing in a contact aureole, as opposed to a regional metamorphic terrain with related plastic movement, such inhomogeneities can be maintained and thereby become significant.

4) The hornblende in this rock-type is a definite dark greeny-brown parallel to Z in marked contrast to the dark green hornblendes of the country rock amphibolites. A similar colour change has been correlated with increase of metamorphic grade by many geologists[1]. According to Binns (1965b)

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[1] E.g. Increase in regional grade:- Wiseman (1934) Scottish Dalradian epidiorites, Shido & Miyashariro (1959) in Abukuma, Engel & Engel (1962) in the Adirondacks, and Binns (1965b) in the Australian Willyama complex.
Increase of grade in contact aureole:- Flett (1915), Green (1964) Lizard area of Cornwall and Binns (1965a).

this colour change is related to an increase in Ti relative to Fe^{3+} in the hornblende. Table 4-3 shows that hornblende from coronite amphibolite No. 474 has $\frac{Ti}{Fe^{3+}} = 0.82$ which compares with a value of 0.32 for green hornblendes from the anorthosite. (Unfortunately I have no data on minerals from the country rock.)

Of all the coronite amphibolites examined, one only showed features that could be interpreted as being due to retrogression[1]: the retrogression in this solitary instance emphasises the lack of it in all the others and is also significant regarding the nature of the coronite. The hornblende, for example, shows a marginal development of optically positive, pale-green, non-pleochroic cummingtonite in almost perfect optical orientation with the hornblende. Further, the hornblende is a dark green variety (not brown) and it contains orientated (exsolved) inclusions of oxide. This supports Binn's hypothesis that the dark-brown colour of the coronite hornblendes is indeed related to the extra Fe (probably ferreous) and Ti that the phase can accommodate at the higher temperature of the aureole. At the lower temperature of this local retrogression the hornblende has reverted. It can also reasonably be induced that this Fe and Ti were probably introduced metasomatically[2] and, because these components have been largely incorporated in the amphibole, this metasomatism is not obvious in hand specimen. Corroborating the retrogression is the absence of pyroxene and the presence of veins of felted biotite cross-cutting all the other minerals.

Genesis of the Coronite Amphibolite

For the garnet ores of the Gore Mountain deposit, which show some features ostensibly similar to the coronite amphibolite, Bartholomé (1960) concludes that the garnet (at the centre of the corona) is growing at the expense of the matrix under conditions of rising temperature but with no

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[1] Note coronite texture itself is retained.

[2] The Lac du Bois amphibolites are typically low in oxides.

TABLE 4-3

Chemical Analysis of a Hornblende from Coronite Amphibolite No. 474

	Wt %
SiO_2	42.99
TiO_2	1.97
Al_2O_3	13.14
Fe_2O_3	2.39
FeO	14.02
MnO	0.15
MgO	10.00
CaO	10.97
Na_2O	2.06
K_2O	0.74
H_2O^+	1.34
CO_2	0.02
Cr_2O_5	0.04
	99.83
Total Fe as Fe_2O_3	18.17

Structural formulae

a) On basis of 24 oxygens

b) On basis of 23 oxygens[Note 1]

	(a)		(b)	
	1.76	Ca	1.74	
X 2.50	0.60	Na	0.59	2.47 X
	0.14	K	0.14	
	1.75	Fe^{2+}	1.73	
	0.02	Mn	0.02	
Y 5.24	2.23	Mg	2.20	5.07 Y
	0.75	Al^{vi}	0.63	
	0.22	Ti	0.22	
	0.27	Fe^{3+}	0.27	
Z 8.00	6.43	Si	6.34	8.00 Z
	1.57	Al^{iv}	1.66	
	1.34	OH	(2.00)	assumed

$$0.82 = \frac{Ti}{Fe^{3+}}$$

Note 1 Calculation on basis of 23 oxygens is presumed to circumvent possible errors in water and fluorine analyses; such errors will seriously affect the structural formula. E.g. it is seen that by assuming 2OH the apportionment of Al to iv - coordination is increased and, due to the subsequent decrease in Al^{vi}, Y approaches closer to ideal value of 5.

componental movement (i.e. we can infer essentially constant pressure). Superficially rather surprisingly, he is at some pains to indicate that such conditions are of regional metamorphic origin and not of contact metamorphic origin[1] as had been suggested by Levin (1950). Anyhow there are sufficient differences in the details that an identical origin is not compelled for the Whitestone coronites and I propose that conditions of rising temperature and essentially constant pressure[2] were provoked by the intrusion of the anorthosite and, accompanied by a percolating fluid phase relatively rich in Fe and Ti, these conditions resulted in the unusual texture and mineralogy of this rock type.

Such a generalisation, while comparatively safe from criticism, is at the same time frustratingly vague as an origin for this remarkable rock-type. Regrettably insufficient data precludes a quantitative, chemical synthesis similar to that carried out for the Gore Mountain garnet deposit by Bartholomé (1960) but, stimulated by some of his concepts, I dare to tentatively advance the following qualitative hypothesis.

Due to a rapidly rising temperature, occasioned by the influx of a hot Fe and Ti-rich fluid phase, the pre-existing upper amphibolite facies assemblage became unstable and reacted according to the following scheme. The amphibole changed in composition, incorporating (at least) Fe and Ti from the fluid phase. At the same time pyroxene began to

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[1] Clearly he feels this is necessary to mesh with Buddington's concept of the regional geology - but I'm not convinced that a contact origin is obviously wholly incompatible with the work of Buddington (Bartholomé's supervisor).

[2] Uniformly increasing hydrostatic pressure would be equally consistent.

develop simultaneous with the breakdown of the garnet to plagioclase, the excess components being absorbed by the pyroxene. These components were transferred along a spherical chemical gradient which, not being continually destroyed by pervasive shearing movements, gave rise to the concentric structures diagnostic of the rock-type. In other words, if this particular reaction had taken place with concurrent shearing movement the resulting texture would give no clue to the participating phases. Obviously many important problems remain but it is futile to speculate further without much more data. The grade of metamorphism of this rock (and the succeeding) will be discussed in section 4e.

4c(ii) Contact Gneisses

On the western side of the anorthosite metasomatism is not obvious in the field but for several feet from the contact the gneisses show features conveniently interpreted as being due to heat dissipated from the anorthosite. In thin section the minerals show less directional features than the extra-aureole migmatites and in general the rocks are somewhat finer grained[1]. Purely textural features, however, are in this case overshadowed by the mineralogy. In these rocks a common assemblage is:-

qtz-plag-Kspar-garnet-cpx-hble-oxides

while in gneisses contiguous on the tail, where the anorthosite is much thinner, clinopyroxene is absent. These granulite parageneses contrast with the upper amphibolite assemblage of the country rocks. Although not obvious in the field the rather high modal opaques (0.5→2%) is

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[1] This is much more noticeable in hand specimen.

indicative of at least some degree of metasomatism.[1] Further, the high modal mafics (garnet + cpx + hble = 30% contrasting with biotite ± garnet = 10% in typical migmatite) suggest that, like the coronite amphibolite, much of the metasomatism is absorbed by the growth of new phases.

In contrast to the coronite the sheer abundance of the small, red, garnet crystals indicates that garnet is growing in this, a much more quartz-rich, bulk composition. Although no mineralogical data is available for these rocks, the common occurrence of garnet as a corona on the oxide phases noted in thin section would seem to indicate that the garnet is almanditic rather than grossularitic. If this is so it corroborates the conclusion (see section 4e) that the rocks of the aureole are more appropriately considered in a Barrovian-type facies scheme than as of true hornfels facies; cordierite should be the stable alumino-ferrous phase in the pyroxene hornfels facies and not almandine. I take this to mean that the anorthosite crystallised at pressures greater than that normally found in the typical hornfels facies; that is, greater than 3.5 — 4Kb. (See Winkler (1967), chapter 6).

The subdued foliation (palimpsestic), the less marked grain-size differential between leucosome and melanosome and the eloquence of the distribution of this rock type are all consistent with these features being imposed on rocks which were already migmatites. Further, there is neither textural nor mineralogical evidence of any metamorphic readjustment subsequent to the development of the granulite facies paragenesis. Similarly the retrogression postulated for one coronite merely emphasises the lack of it in all the others.

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[1] Gneisses outside this narrow zone carry only trace amounts (<0.1%) of opaques. See Table B-4.

4d. The Metasomatic Aureole

The field characteristics of these rocks were described in chapter 3 and their superficial similarities, their heterogeneity and their field distribution were shown to be compatible with their origin as metasomatised gneisses of divers original composition. In this section their petrography and bulk chemistry will be shown to be wholly consistent with such an interpretation. Table B-2 (Appendix) lists modes of the rocks studied.

Fig. 4-2, for example, illustrates both their heterogeneity and the remarkable richness in garnet and oxides which distinguish these rocks from the country rock proper. Chemical analyses of six of these rocks are collected in table 4-4 all showing unusually high, but variable, total Fe+TiO_2 relative to both SiO_2 and MgO.

Over and above the expected modal differences (Fig. 4-4) those rocks representing metasomatised amphibolites can be distinguished from the metasomatised migmatites and gneisses on textural features. These latter felsic gneisses retain evidence of a previous foliated texture, although they are all recrystallised to varying degrees. The minerals, especially the hornblendes, are elongate and crudely aligned; similarly the quartz is often in folia. Gneissic and migmatitic banding are still apparent. [The more mafic amphibolites, by contrast, are characterised by a compact, fine-grained texture in which the majority of the crystals (of all phases) have polygonal outlines and are approximately equigranular. No remnant of a foliation remains except for relatively large scale compositional banding] Quick

1 X

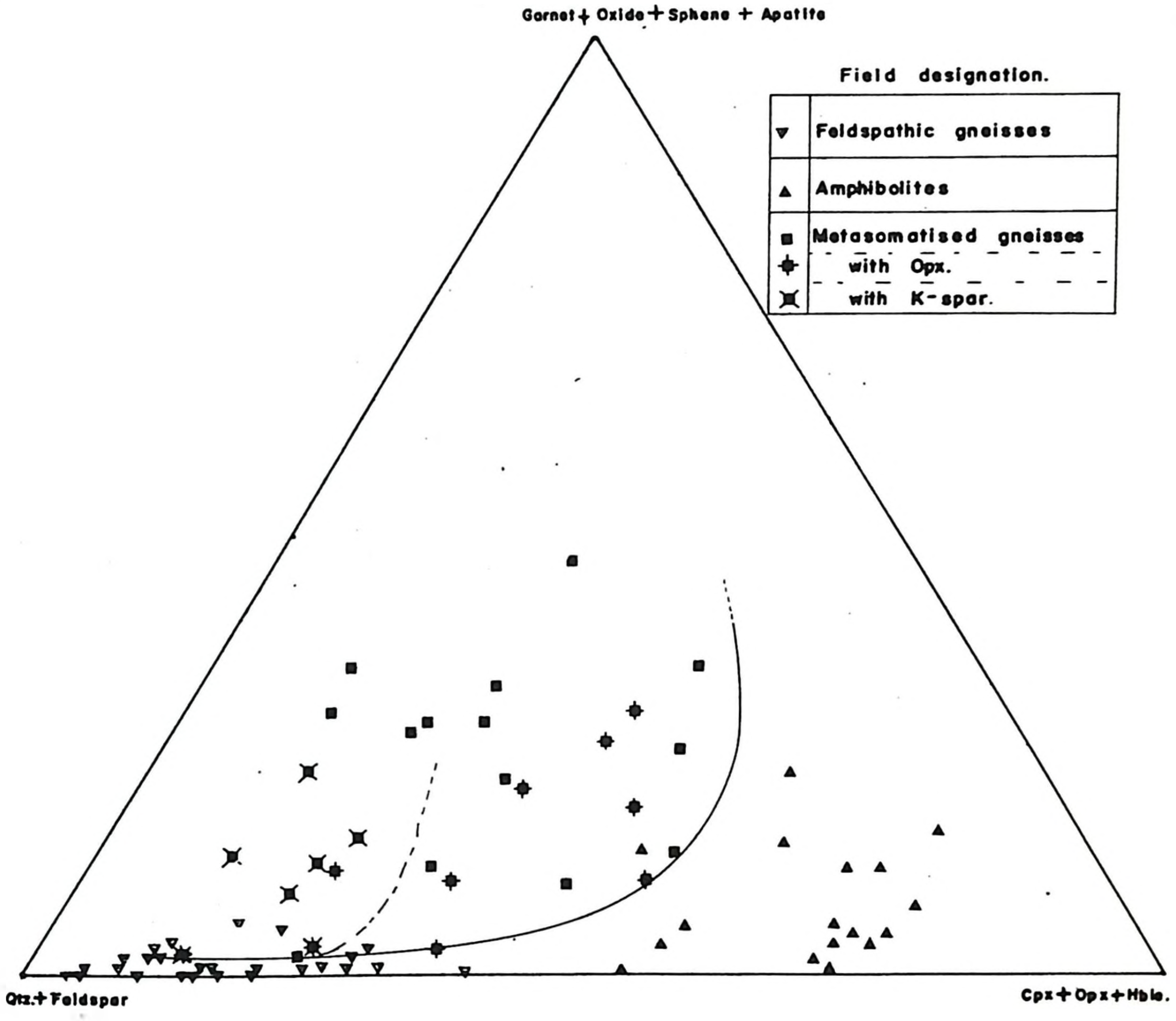

FIG 4-2. Plot of modal data for envelope rocks of the Whitestone anorthosite.

TABLE 4-4

Chemical Analysis of Metasomatised Gneisses from the Aureole of the Whitestone Anorthosite

Lab No	482	483	425	494	495	480
Field No	L3-102	L3-100	L3-77	L3-94	L3-95	L3-105
SiO_2	45.56	49.54	56.95	58.36	59.25	60.67
TiO_2	3.26	1.08	2.05	2.11	0.86	1.65
Al_2O_3	12.43	19.31	11.84	12.63	13.68	12.43
Fe_2O_3	19.27*	3.00	6.86	15.27*	8.78*	12.71*
FeO		7.21	7.65			
MgO	3.86	4.81	1.87	1.75	4.77	1.20
CaO	11.91	9.07	6.78	7.04	7.00	5.44
Na_2O	2.20	3.86	2.96	2.00	3.97	3.54
K_2O	0.29	0.57	0.45	0.42	0.58	1.44
Total	98.78	98.45	97.39	99.58	98.89	99.08
Total Fe as Fe_2O_3	19.27	11.01	15.36	15.27	8.78	12.71

*Total Fe as Fe_2O_3

Analysts - I.M. Mason & J. Muysson

1) Because all the gneisses are rusty in hand specimen FeO, where analysed, can only be considered as a minimum value. In the original rock it was probably higher.

2) Because H_2O and P_2O_5 were not determined all the totals, as expected, are low.

I believe this polygonal texture to be the result of a thoroughgoing recrystallisation which has affected the mafic amphibolites more completely than the acidic rocks. The reason for this is presumed to be the greater 'porosity' of the amphibolites to the metasomatising fluids due to their original richness in the inherently reactive hydrous mafic minerals (as discussed in chapter 3) and that these hot fluids have greatly enhanced the efficacy of the recrystallisation. Moreover, I take the polygonal texture as further evidence of the lack of differential movement during the recrystallisation.

The type assemblage in the metasomatised amphibolites is:-

plag-cpx-hble-garnet-oxide + trace amounts of apatite ± qtz.

Virtually all the rocks contain at least these phases. However, several samples also contain pleochroic orthopyroxene. The presence of this phase does not appear related to distance from the anorthosite since 498, without orthopyroxene, is much closer to the pluton than 493, which does contain orthopyroxene. As mentioned in section 4c very local compositional differences are thought to be important.

In thin section the following points can be noted:-

1) The rocks are generally fine-grained, 0.1-0.3 mm is typical. However, the garnet may occur in grains up to 3 mm.
2) Each garnet crystal invariably contains at least one rounded bleb of oxide. Garnet is usually the most irregularly shaped mineral in the thin section and this shape is apparently controlled by the oxide minerals.
3) Clinopyroxene, orthopyroxene and garnet are usually so

intimately intergrown that it is difficult to interpret their mutual textures. Typically, the green clinopyroxene occurs as polygonal grains both surrounding and intergrown with the garnet and as distinct grains. In some cases the orthopyroxene, if present, occurs as if it is replacing the clinopyroxene but it also occurs as distinct grains wholly similar in range of habit to the clinopyroxene.

4) In several cases greeny-brown veins, wholly similar to those in the green feldspar facies of the anorthosite, occur along the interfaces of the plagioclase grains. The plagioclase itself is also typically polygonal.

5) A signal feature is the abundance of rounded blebs of oxide which occur interstitially throughout the rock.

6) Apatite, occurring interstitially, is a constant accessory. In those few cases where the rock lacks a pyroxene phase apatite is much more abundant. E.g. No. 478 with the assemblage plag-hble-garnet-oxide contains 3% modal apatite which contrasts with the trace amounts in the other, pyroxene bearing, varieties.

7) Hornblende is present in all rocks to varying degrees, occasionally as noted above, to the exclusion of both pyroxenes. It is important to note that the hornblende does not show textures which can be satisfactorily explained on the basis that the hornblende is secondary and due to a later metamorphic event. In fact in thin section it occurs both intergrown with the other mafics and as discrete

grains: it does not, for example, invariably, or even usually, occur rimming the other mafics. Note also rock 478 with no pyroxene occurs interbedded with pyroxene-bearing 477, 478 being three times richer in apatite. I suggest that these facts are consistent with the existence of rapid, local fluctuations in the fugacity of the fluid phase. In general, as is compatible with the concept of a metasomatism, this fugacity was relatively high. (For a discussion on the role of hornblende in granulite facies rocks see Buddington (1963) and de Waard (1965 & 1966)).

8) Biotite, if present, usually occurs as stellate clusters radiating out from the less hydrous mafic minerals. The rarity of biotite (present in only 5/33 cases) plus the non-directional habit indicates that retrogressive effects are local: it is difficult to ascribe them to a regional metamorphic event.

In the more felsic gneisses the typical assemblage is:-

qtz-plag-Kspar-cpx-hble-garnet-oxide ± trace apatite.

That is similar to the amphibolites with the addition of essential quartz and K-spar. In these rocks also orthopyroxene may or may not be present and, except for the lack of polygonal texture, paragenetic relations are similar to those in the metasomatised amphibolites.

It seems relatively clear that the sum total of the field and petrographic features of these rocks can be satisfactorily explained on the basis that an originally diverse series of rocks, ranging in composition from acidic gneisses to amphibolites, were subjected to the concerted action of heat and fluids rich in Fe, Ti, H_2O and P_2O_5[1] and that both these emanated from the anorthosite.

Moreover, as noted in several places above, there is a notable lack of evidence of any metamorphism subsequent to the development of the contact rocks. Of course the possibility remains, and this I consider most likely, that the anorthosite was intruded and the aureole developed during the final stages of the last metamorphism of any consequence to affect the area[2]. The problem of whether this final metamorphism was of Penokean or Grenville age remains for the isotope-geochemists to haggle over. (Compare discussion in section 4e.)

It is interesting to note that, if instead of having been imposed on rocks of widely varying composition, the metasomatism had acted on rocks originally relatively uniform (say a syenite-gneiss) then these rocks might be expected to show a gradation in composition, mainly in Fe, from those areas most severely affected to those unaffected. Such a gradation may possibly have many of the hallmarks of an igneous variation. Furthermore, the polygonal, non-directional fabric which tends to be developed could perhaps be mistaken for an igneous texture modified by a later metamorphism.

4e. Metamorphic Grade in the Aureole

The details of the metamorphism developed in the aureole of the Whitestone anorthosite raises various problems concerning the vexatious

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[1] It is not clear from the data available whether elements other than these played an important part in the metasomatism.

[2] Because of the activation energy involved it is theoretically sound to suppose that, in general, equilibrium conditions must be exceeded before a reaction can proceed at a finite rate. It follows, therefore, that retrogressive type reactions are more likely to occur during a subsequent heating up rather than during the initial cooling off. The generally more hydrous nature of the lower grade phases also prohibits reaction during the cooling-off cycle unless there is access to extraneous H_2O. The rare retrogression noted may have resulted in this way due to local pockets of H_2O during the cooling off.

granulite facies. These inherent problems are, in the Whitestone aureole, compounded by the influence of a widespread metasomatism.

A survey of the literature on the granulite facies (see e.g. references in Green & Ringwood (1966) and also Himmelberg & Phinny (1967) and Singh (1966)) indicates that it is probably reasonable to assume there exists granulites of low, medium and high pressure, these being defined on the basis of the following criteria:-

Low pressure granulites - characterised by olivine and plagioclase and cordierite.

Medium pressure " - characterised by association orthopyroxene-plagioclase and the incompatibility of both olivine-plagioclase and clinopyroxene-garnet-quartz.

High pressure " - characterised by association clinopyroxene-garnet-quartz and incompatibility of hypersthene-plagioclase.

The relations for the medium and high pressure varieties are summarised in the idealised A.C.F. diagrams shown as A and B, fig. 4-3.

In a discussion of the granulite facies in the Adirondacks de Waard (1965) notes that the majority of the rocks studied showed assemblages consistent with fig. 4-3A. However, the so-called Woolen Mill gabbro, which occurs as an inclusion in the Adirondack anorthosite near Elizabethtown N.Y. shows the assemblage clinopyroxene-garnet-quartz.

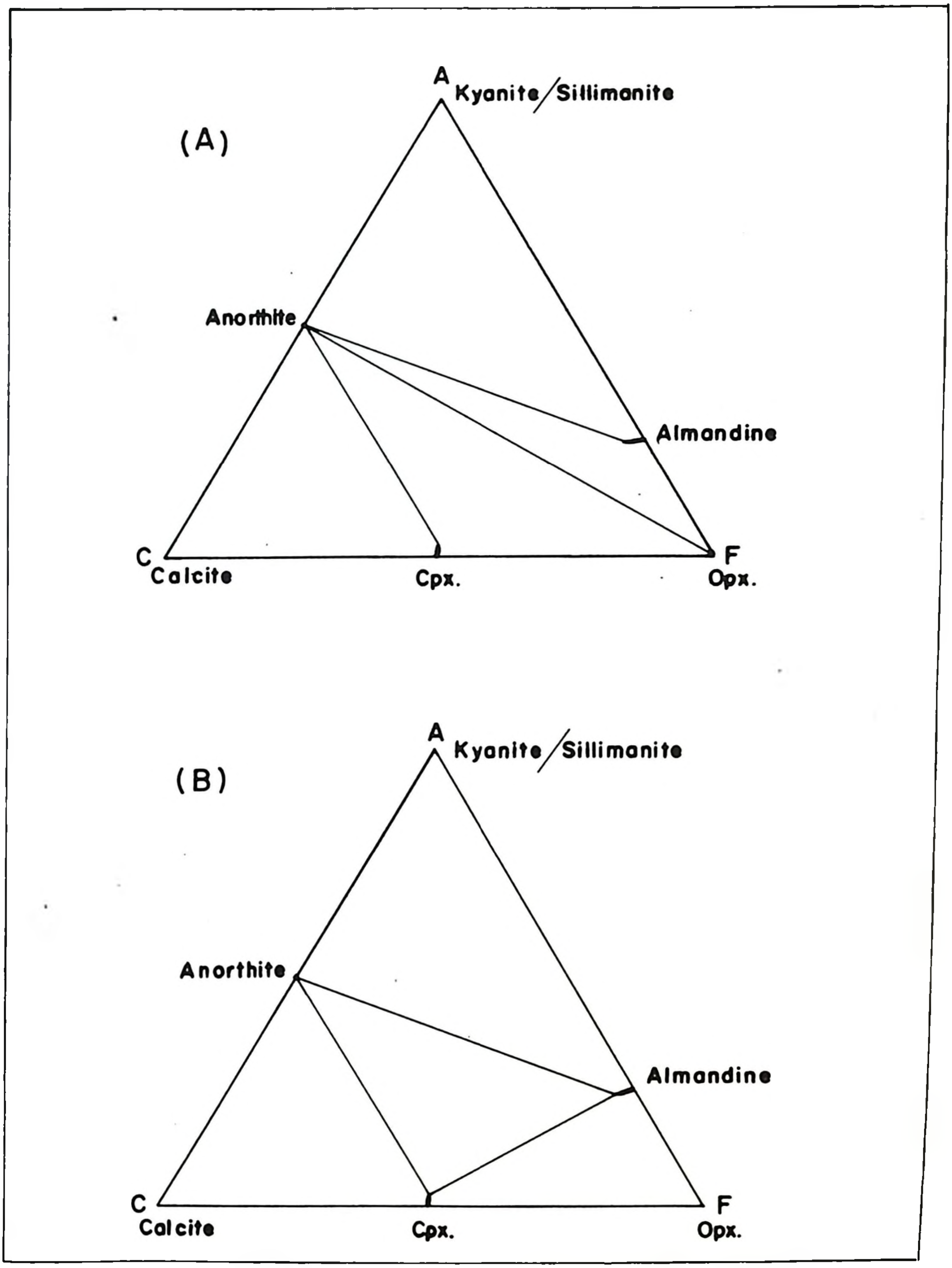

FIG. 4-3. Phase relations in the granulite facies.

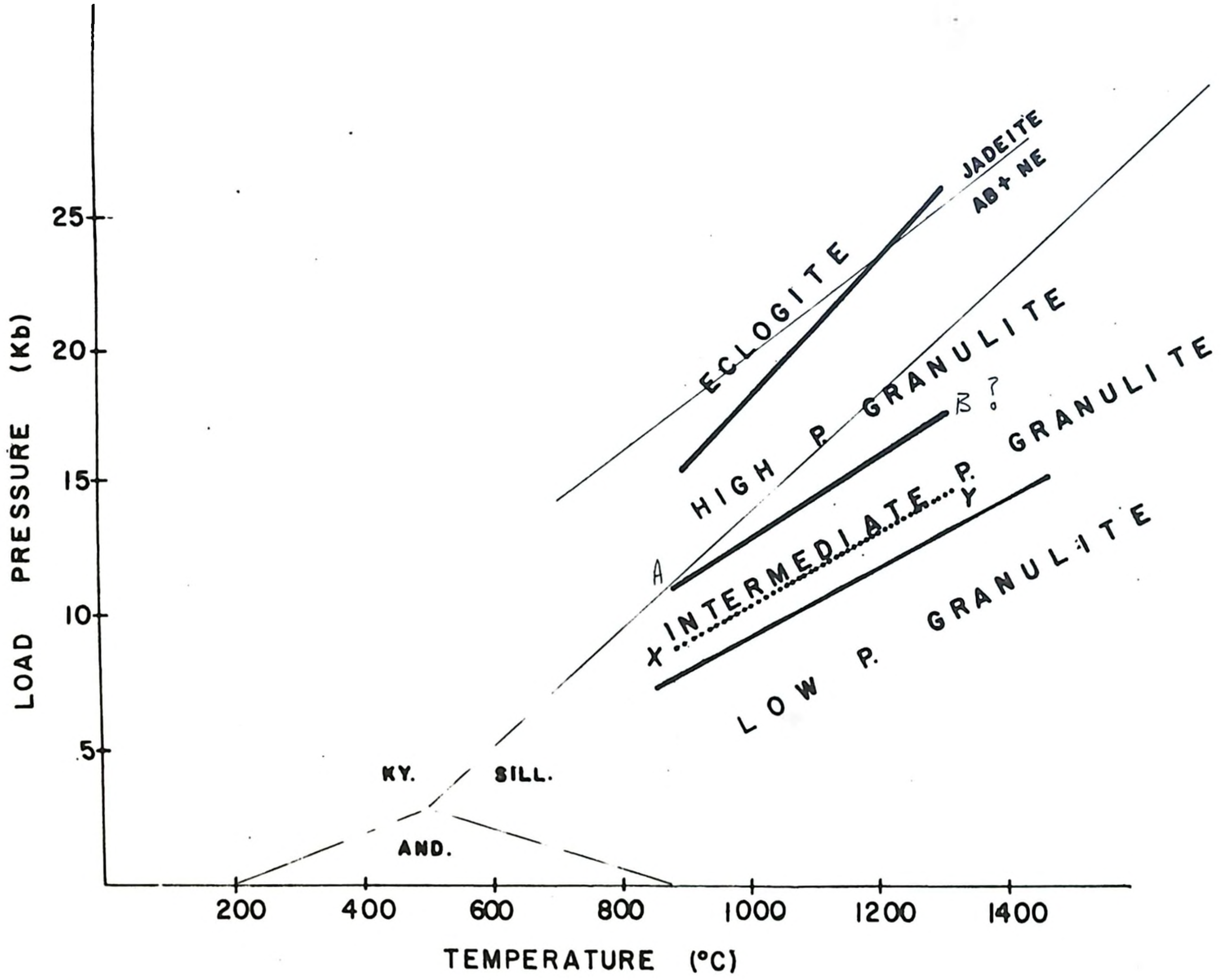

FIG 4-4. Classification of the granulite facies after Green & Ringwood (1966).

He notes that in a reaction of the type

$$\text{opx} + \text{plag} \rightleftharpoons \text{cpx} + \text{alm} + \text{qtz}$$

for the mineral compositions appropriate to this rock, there is a reduction of molar volume of about 14% going to the right. He therefore proposes that this Woolen Mill gabbro recrystallised under higher load pressure than was normal for the other granulites of the Adirondack Highlands. Green & Lambert (1965) and Green & Ringwood (1966) have experimentally confirmed this phase transition for anhydrous granitic and basaltic compositions respectively. Fig. 4-4 summarises the experimental results of Green & Ringwood for saturated basaltic compositions and it is noted that this diagram is consistent with de Waard's proposal. However, particular attention is drawn to the line XY on fig. 4-4 which has been transferred from fig. 7 of Green & Ringwood's paper and has been extrapolated slightly in a direction parallel to the line separating medium from high pressure granulites[1]. This line represents the first appearance of the assemblage garnet-clinopyroxene-quartz, i.e. equivalent to line AB, in rocks with the unusually low ratio $\frac{100\ \text{Mg}}{\text{Mg} + \text{Fe}^{2+}} = 10$. For a typical quartz tholeiite this ratio is about 60; this is the value appropriate to line AB.

many of these experiments had H_2O present.

I have collected a specimen of the Woolen Mill gabbro and, both in hand specimen and petrography (excluding modal abundances), find it to be indistinguishable from the more mafic of the metasomatised gneisses of the Whitestone area in which the assemblage clinopyroxene-garnet-quartz orthopyroxene is also very common. Similarly, I have collected a specimen of the Tupper-Saranac syenite complex from a quarry on Route 3

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[1] Note that due to extensive solid solutions in the natural case the lines AB, XY etc. will be rather diffuse.

TABLE 4-5

Chemical Analysis and Modes of three granulites with assemblage Cpx-garnet-qtz ± opx.

	A	B	C
SiO_2	47.16	53.35	56.95
TiO_2	3.37	1.38	2.05
Al_2O_3	14.45	14.97	11.84
Fe_2O_3	1.61	3.31	6.86
FeO	13.81	10.61	7.65
MnO	0.24	-	-
Mgo	5.24	1.72	1.87
CaO	8.13	6.43	6.78
Na_2O	3.09	3.50	2.96
K_2O	1.20	3.74	0.45
H_2O	0.48	0.14	-
P_2O_5	0.57	0.70	-
Total	99.35	99.86	97.39

$\frac{100/Mg}{Mg+Fe^{2+}}$	40	21	26

A. Woolen Mill Gabbro.
Elizabethtown N.Y.
Analyst W.F. Hillebrand.
Reference Buddington 1939.

B. Almanditic ferroaugite syenite gneiss.
Quarry N.E. of Moody Lake, Saranac Lake N.Y.
Analyste L.C. Peck.
Reference Buddington 1939.

C. Metasomatised Gneiss No. 425.
Whitestone Area.
Analysts, I.M. Mason & J. Muysson.
New analysis.

	Mode		
	A	B	C
Qtz	0.8	3.4	39
Kspar	1.8	39.2	Tr
Plag	40.9	22.7	36
Hble	0.2	0.4	11
Opx	-	2.8	-
Cpx	24.1	12.6	2
Gt	20.7	8.0	5
Oxide + Apatite	11.5	10.3	7

approximately 1½ miles east of Tupper. This rock is presumed to be similar to the syenite gneiss whose analysis is tabulated by Buddington (1952). Again in both hand specimen and thin section the petrography[1] is identical to rocks of equivalent composition in the Whitestone metasomatic aureole. Chemical analyses, modes and the ratio $\frac{100\ \mathrm{Mg}}{\mathrm{Mg} + \mathrm{Fe}^{2+}}$ are given in table 4-5 for these two Adirondack rocks plus a rock from the Whitestone area: the relatively low $\mathrm{Mg/Fe}^{2+}$ ratio is noted. (It should also be recognised that all the rocks in table 4-5 show rusty-weathering so that the FeO is probably underestimated, consequently the original $\frac{100\ \mathrm{Mg}}{\mathrm{Mg} + \mathrm{Fe}^{2+}}$ ratio may have been considerably lower than indicated).

I propose, therefore, that the development of the assemblage clinopyroxene-garnet-quartz ± orthopyroxene, found in the aureole of the Adirondack and Whitestone anorthosite is controlled by the bulk composition of the system and, in particular, by the unusually low $\mathrm{Mg/Fe}^{2+}$ ratio. In effect this proposal replaces the rather ad hoc assumption of de Waard that the granulite facies developed round anorthosites is of a higher pressure than other granulites in the same region with the assumption that the rocks recrystallised round anorthosites are subject to a lower Mg/Fe ratio than other rocks. I suggest the present thesis gives independent credence to this latter proposal.

It is perhaps significant to note that an ACF plot of such rocks does not adequately demonstrate this iron enrichment because much of the extra Fe is present in the 'accessory' minerals[2], magnetite and ilmenite, and this Fe is subtracted from the F-parameter prior to calculating the

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[2] Note high proportion of oxides in modes in table 4-5.

[1] i.e. In all aspects of petrography except details of mode.

rock's ACF composition.

4f. Comparison with other Anorthosites

As insinuated in the text of the preceding section and by table 4-5, I have suggested that the Adirondack anorthosite may also possess a metasomatic aureole similar to that of the Whitestone anorthosite. The metasomatism is presumed to have affected, in particular, the syenites of the Tupper-Saranac complex, fig. 4-4. This implies that the syenite is older than the anorthosite, a thesis which, in effect, completes the trilogy of possibilities for these rocks which currently are considered a) younger than the anorthosite (Buddington 1939,1952,1966) or b) coeval with the anorthosite (Balk 1931, de Waard 1966).

With but few exceptions, published studies concerning anorthosites tend to ignore the details of the anorthosite-country rock relations. However, many authors have noted and commented on the frequent coincidence of anorthosite and pyroxene-syenite. This juxtaposition has been emphasised to such an extent that it is now respectable to hold that the anorthosite and the 'syenite' are comagmatic (see Green 1966 e.g.).

Table 4-6, painfully extracted from the meagre data available, is an attempt to indicate that the condition valid for the Whitestone anorthosite may be of more general significance and I suggest that as a result of the present thesis these contact relations are worthy of further study. I do not, of course, categorically deny a possible genetic relationship between the anorthosite and the acidic rocks in all cases. However, I do submit for consideration that many geologists have biased their thinking by viewing the circum-anorthosite rocks in such

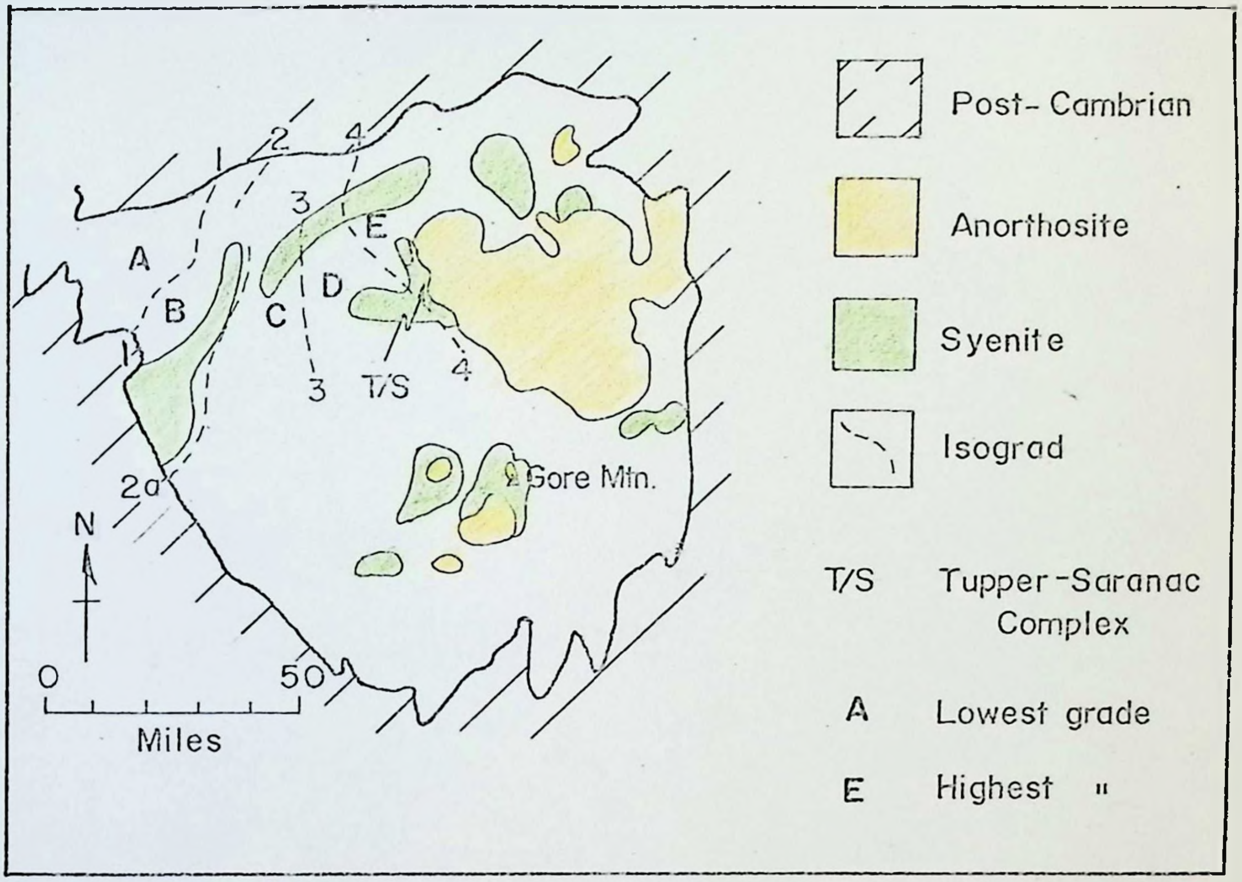

FIG. 4-5. Sketch map of some Pre-Cambrian rocks of the Adirondacks.

Isograds. (After Buddington 1963, 1965.)

1) Garnet first appears in biotite-quartz-plagioclase gneiss
i.e. zone B.

2) Orthopyroxene first appears as major mafic mineral (in addition to clinopyroxene + hornblende) in amphibolitic layers in paragneiss.

2a) Orthopyroxene first appears as major mafic mineral in amphibolitic orthogneiss.

3) Garnet first appears in meta-gabbro gneiss, amphibolite and diorite gneiss.

4) Garnet first appears in syenite-quartz syenite gneisses.

TABLE 4-6

ANORTHOSITE/ENVELOPE RELATIONS IN OTHER AREAS

1)	S.E. ONTARIO
(a)	Regional Metamorphic Grade: Assemblages in feldspathic gneisses include - garnet, biotite, amphibole or pyroxene. p.1404.
(b)	Grade of Contact Metamorphism: Recognised but not discussed in detail. Amphibole and scapolite developed in marble. p.1423.
(c)	Metasomatism: Not recognised. However "the granite is enriched in titaniferous magnetite towards the anorthosite." p.1423.
(d)	Reference: Harrison (1944)
2)	NAIN
(a)	Regional Metamorphic Grade: Granulite facies. e.g. "association of hypersthene and orthoclase occurs but rarely. The characteristic association of hypersthene and augite is common. Garnet uncommon." p.1756.
(b)	Grade of Contact Metamorphism: Few contact metamorphic phenomenon definitely attributed to anorthosite. At one locality cordierite hypersthene occurs in the adamellite gneiss. p.1759. Also notes that hypersthene in the fayalitic adamellite is restricted to the junction with the anorthosite. p.1760.
(c)	Metasomatism: Not recognised. However "in many rocks (adamellites) of "hypersthene facies" there is high content of black ore." (1955) p.1042. Wheeler also notes that an oxide rich tyro pyroxene meladiorite occurs at the contact of the anorthosite and the adamellite.
(d)	Reference: Wheeler (1955) " (1960)

3)	INDIAN HEAD
(a)	Regional Metamorphic Grade: "The degree of metamorphism found in these rocks is considerable though not of the most intense type." p.43. ?Upper amphibolite?
(b)	Grade of Contact Metamorphism: Not recognised as such.
(c)	Metasomatism: Authors mention granoblastic norite gneiss which occurs as skin on anorthosite: it is one of two rock types in area that contain commercial magnetite deposits. p.44.
(d)	Reference: Hyle & Ronan (1954)
4)	SEPT-ILES
(a)	Regional Metamorphic Grade: Not discussed. However, notes assemblages - Banded paragneiss garnet. Amphibolites with hornblende and augite in equal proportions. ?Upper amphibolite? p.12.
(b)	Grade of Contact Metamorphism: As anorthosite is approached granite gneiss grades into augen-gneiss; eyes increase in size as anorthosite is approached. Suggests this is due to contact effect. p.12.
(c)	Metasomatism: Notes: "bodies of ferriferous gabbro such as form the marginal portion of the anorthosite over large stretches." Analyses given indicate these rocks contain between 15-20% Fe. Note he suggests "gabbro" is not related to anorthosite. p.25.
(d)	Reference: Faessler (1942)
5)	ST. URBAIN
(a)	Regional Metamorphic Grade: Not discussed. However notes assemblages - quartz-plagioclase-Kspar-biotite hornblende - garnet noted in some gneisses. Garnet also common in dark green feldspar (sic) granites. ?Upper amphibolite or granulite?
(b)	Grade of Contact Metamorphism: Not recognised.
(c)	Metasomatism: "In places it seemed iron ore content increased in vicinity of anorthosite." p.13. see also pp.28-29.
(d)	Reference: Mawdsley (1927)

6) ALLARD LAKE

(a) Regional Metamorphic Grade: No rocks older than anorthosite mapped in this study. He notes, however, that dominant rock of area is hornblende and biotite granite which is locally poor in quartz and is therefore syenite. p.178.

(b) Grade of Contact Metamorphism: Notes syenite near anorthosite is pyroxene bearing (clino + ortho). p.178.

(c) Metasomatism: "Contact relations between anorthosite massif and surrounding pyroxene syenite are complicated by the apparently ubiquitous occurrence of a mafic rich zone between the two." Enrichment is magnetite which shows up as a striking aero-mag. anomaly. p.178.

(d) Reference: Hargraves (1962)

7) ADIRONDACKS

(a) Regional Metamorphic Grade: Because of apparent convergence of regional isograds (see fig. 4-7) with expected aureole of anorthosite the two are difficult to separate. However, seems certain that regional grade in vicinity of anorthosite is high - probably hornblende-granulite grade. Area D, fig. 4-7.

(b) Grade of Contact Metamorphism: Most detail paid to contact of marble and anorthosite and is more relevant to metasomatism. However, note two pyroxene garnet syenite gneisses mentioned in last section of this work.

(c) Metasomatism: Skarns at marble contacts largely composed of andradite-hedenbergite, wollastonite - which bespeaks large Fe metasomatism. Oxide rich rocks at contact are of common occurrence: also compare section on metagabbros, p.64. "Mafic metagabbro, rich in ilmenite-magnetite, is present locally within the metagabbros along the east side of the anorthosite. These mafic facies all occur in metagabbros which either directly overlie the Anorthosite or where ...... position close to the anorthosite may be reasonably inferred. p.64.

(d) Reference: Buddington (1939)
" (1952)

igneous-implicated terms as syenite and adamellite[1] and I propose that perhaps a different slant is achieved by wondering at the common association of anorthosite with oxide-rich, clinopyroxene-garnet acidic gneisses.

4g. Significance of Age of the Adirondack Anorthosite

As noted in section 1b(iv) anorthosites have proved intractable to current isotopic dating techniques and, to short circuit this refractiveness, several workers have dated the Tupper-Saranac complex assuming it to be genetically related, i.e. therefore coeval, with the anorthosite. Silver (1966), using zircons from the syenite, obtained an age of 1125 m.y. which is older than the metamorphic age for the area of 1090 m.y.. Using whole rock Rb/Sr, Heath (1967) obtained an age for the same syenite of 1055 m.y. or 1000 m.y. depending on decay constant used.

On the basis that the Tupper Saranac complex has been thoroughly metasomatised at granulite facies grade by the anorthosite then these divergent ages can be reconciled. I propose that the zircon age of 1125 m.y. represents the age of intrusion of the syenite (i.e. older than the metamorphism); the subsequent intrusion of the anorthosite at 1055 m.y. or 1000 m.y. has, due to the metasomatism, successfully reset the Rb/Sr clock by re-equilibrating over the whole body - the zircons being immune to this re-equilibration. This age of intrusion of the anorthosite, after the main metamorphism, is qualitatively the same as that proposed for the Whitestone anorthosite in this thesis.

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[1] It may not be irrelevant to note that several authors have note either explicitly or implicitly, that while the anorthosite itself is to a large extent rich in igneous structures and may be largely massive the accompanying acidic gneisses, which may be of equivalent areal extent, are usually gneissic with no well-developed igneous structures.

- there are now lots of examples with ig features 1982

CHAPTER 5

THE PETROGRAPHY OF THE ANORTHOSITE

5a. Introduction

To recapitulate the essential points in the argument so far introduced the following are noted:-

1) Glomeropoikilitic texture was interpreted to be igneous in origin and to be an exaggerated manifestation of the typical poikilitic texture.
2) The porphyritic texture (and related block structure) was interpreted as igneous banding, implying that crystal accumulation was operative at least at some stages during the crystallisation.
3) During the crystallisation an iron-rich fluid phase was developed. As well as metasomatising the surrounding rocks it was suggested that this fluid phase has been active within the anorthosite accounting for the anomalies of the green feldspar facies and the distribution of the oxides which, in turn, determines the distribution of garnet and epidote.
4) No recognisable metamorphism has affected the area subsequent to the development of the aureole which implies, since the intrusion of the anorthosite; therefore development of garnet and epidote in the anorthosite cannot be ascribed to a later, independent metamorphism.

Excepting 4) these conclusions have been deduced from observations in the field. In this chapter petrographic, mineralogical and chemical data to buttress these arguments will be presented. In essence the mineral composition of this body is simple and can be considered in terms of three primary phases each with an associated secondary phase. These pairs are plagioclase-scapolite, clinopyroxene-hornblende and oxide-garnet/epidote. Other phases such as apatite, calcite, serpentine, quartz and orthopyroxene are of restricted occurrence only. These will be discussed in the order given, concentrating on features relevant to the petrogenesis of the anorthosite.

5b. Plagioclase-Scapolite

Obviously these phases are the most abundant in the anorthosite and fig. 5-1[1] illustrates both this abundance and its variation over the body. Superficially this diagram could be interpreted to indicate that the core of the anorthosite is less mafic than the margins which would agree with the conclusions of Buddington (1939), Hargraves (1962) and Berrange (1965); however, in this chapter several points will be made which tend to modify such a conclusion: this point will be returned to at the end of the chapter.

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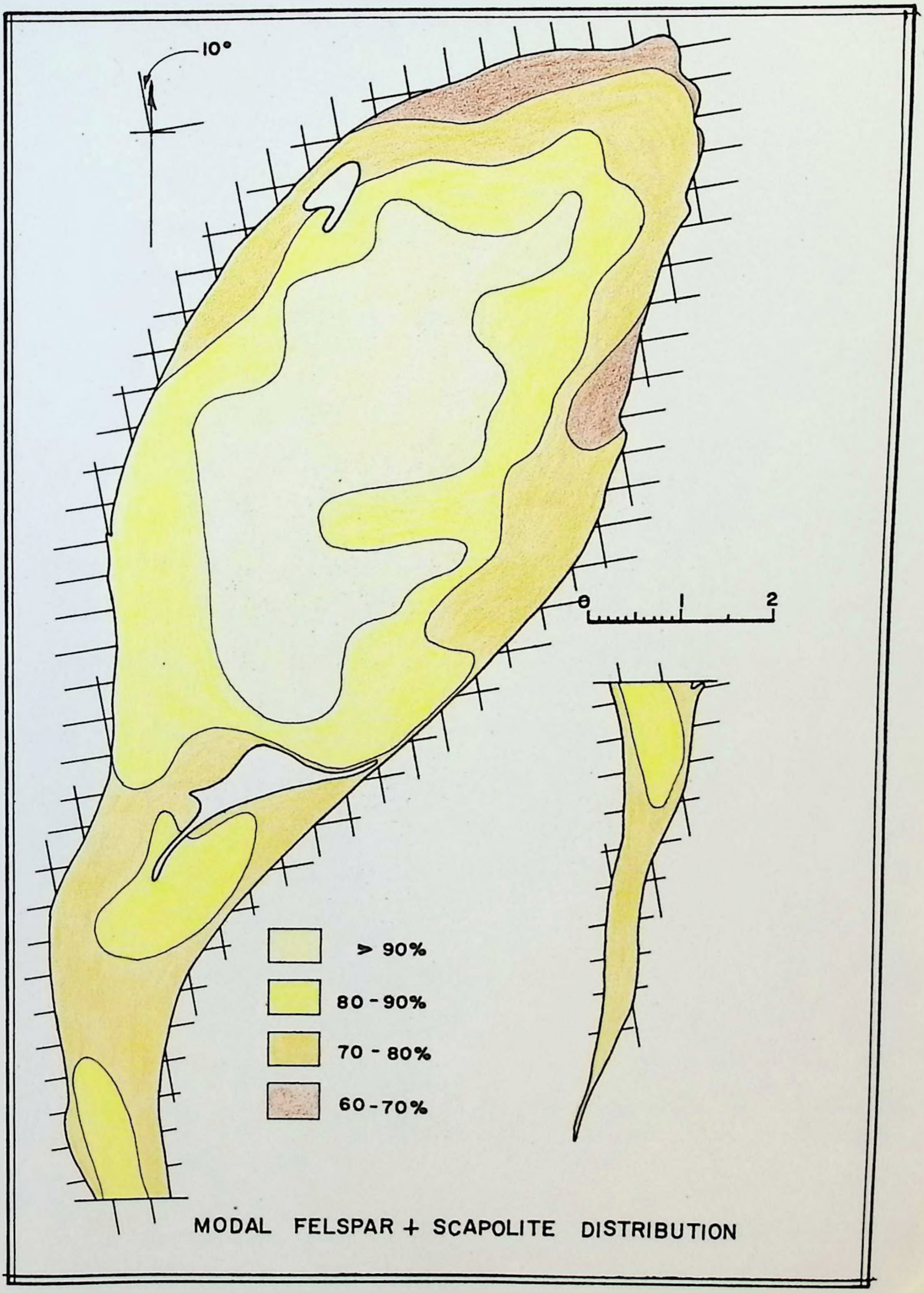
[1] Construction of Fig. 5-1: The data for this and other modal diagrams are based on modal analyses of 340 thin sections distributed as on Map 2-a (back pocket), the actual analyses being tabulated in Table B-1 (Appendix). Plates 2-1, 2 and 3 indicate that the anorthosite, especially the glomeropoikilitic facies, is inhomogeneous on the scale of a thin section (4 x 2.5cm.). To alleviate this the individual modes falling within the superimposed grid-squares indicated on fig. 5-1 were averaged; contours were hand drawn assuming the centre of each square to have the average for that square. Except in poorly exposed areas at least 3 modes were averaged. No weight is attached to the details of the contours in either this or other modal diagrams. Comparison of norms and modes given in Appendix indicate that, in general, agreement is better than might be expected between bulk rock and even individual thin-sections.



MODAL FELSPAR + SCAPOLITE DISTRIBUTION

Fig. 5-1

5b(i) Analytical Techniques

A main goal of the study was to establish the distribution of any significant chemical change in the primary minerals. For the plagioclase the well-known, rapid, simple Michel-Lévy method was selected as most convenient towards this end[1]. Excepting the margins, where the plagioclases tend to be strained, plagioclases in all rocks are extremely well twinned in both the albite and pericline laws - combined Carlsbad-albite twinning was not observed. Agreement of optical values with the wet chemical analyses of three samples given in Table 5-1 are good. In Table 5-2 the microprobe analyses of 17 samples are compared with the optically determined values. From these comparisons it seems safe to assume the Michel-Lévy method to be significant to better than ± 5 An% with the values tending to be on the low side.

5b(ii) Plagioclase Composition in the Anorthosite

The optically determined An content of 240[2] plagioclases (Table 3-1) range from An_{44}-An_{66}. Plotted on a map of the body it will be seen that the lower values are concentrated on the margins and the higher values in the core. An empirically selected contour of $An_{57.5}$, drawn as in fig. 5-2, contains within it 143 An values, 94% of which are in fact greater than $An_{57.5}$; similarly, 91% of all values outside this contour are indeed lower than $An_{57.5}$. This is illustrated in fig. 5-3. Allowing for the uncertainty in the An determination, fig. 5-2 illustrates that

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[1] See Smith, Appendix 3 in Hess (1960), for details of method and precautions that must be taken to ensure accuracy in universal stage measurements. From this description the tremendous increase in labour over the Michel-Lévy method can be easily gauged.

[2] Because of strain and flexed twins it did not prove possible to obtain a valid series of extinction readings on all 360 slides.

TABLE 5-1

Chemical Analyses, Structural Formulae and β and Γ Parameters for three Plagioclases

Lab No	233	230	133
Field No	L1-T-11	L1-T-8	LO-T-31
SiO_2	54.30	52.59	52.77
TiO_2	0.03	0.02	0.02
Al_2O_3	28.92	30.16	30.16
Fe_2O_3	0.20	0.14	0.18
MgO	0.15	0.29	0.00
CaO	11.48	12.03	12.35
SrO	0.072	0.076	0.084
Na_2O	4.05	4.11	4.05
K_2O	0.49	0.46	0.30
Total	99.70	99.88	99.91
Structural Formulae on basis of 32 oxygens			
Si	9.83	9.54	9.57
Ti	0.00(4)	0.00(3)	0.00(3)
Al	6.17	6.45	6.45
Fe^{3}	0.03	0.02	0.02
Mg	0.04	0.08	-
Ca*	2.23	2.35	2.41
Na	1.42	1.45	1.42
K	0.10	0.11	0.07
Mol % An	59.9	60.9	61.8
Ab	37.5	36.3	36.4
Or	2.6	2.8	1.8
composition determined optically	An_{58}	An_{60}	An_{59}
** β	0.88	0.84	0.86
*** Γ	0.72	0.74	0.80

Analyst: J. Muysson,
McMaster University.

*Includes SrO

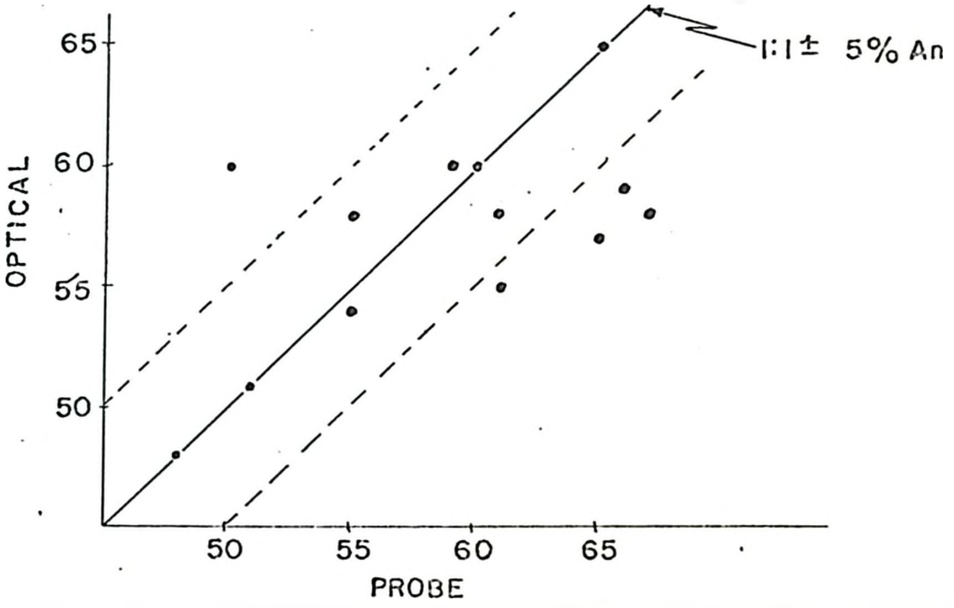
** $\beta = 2\theta(\bar{1}11) - 2\theta(20\bar{1})$ (Smith & Gay 1958)

*** $\Gamma = 2\theta(131) + 2\theta(220) - 4\theta(1\bar{3}1)$

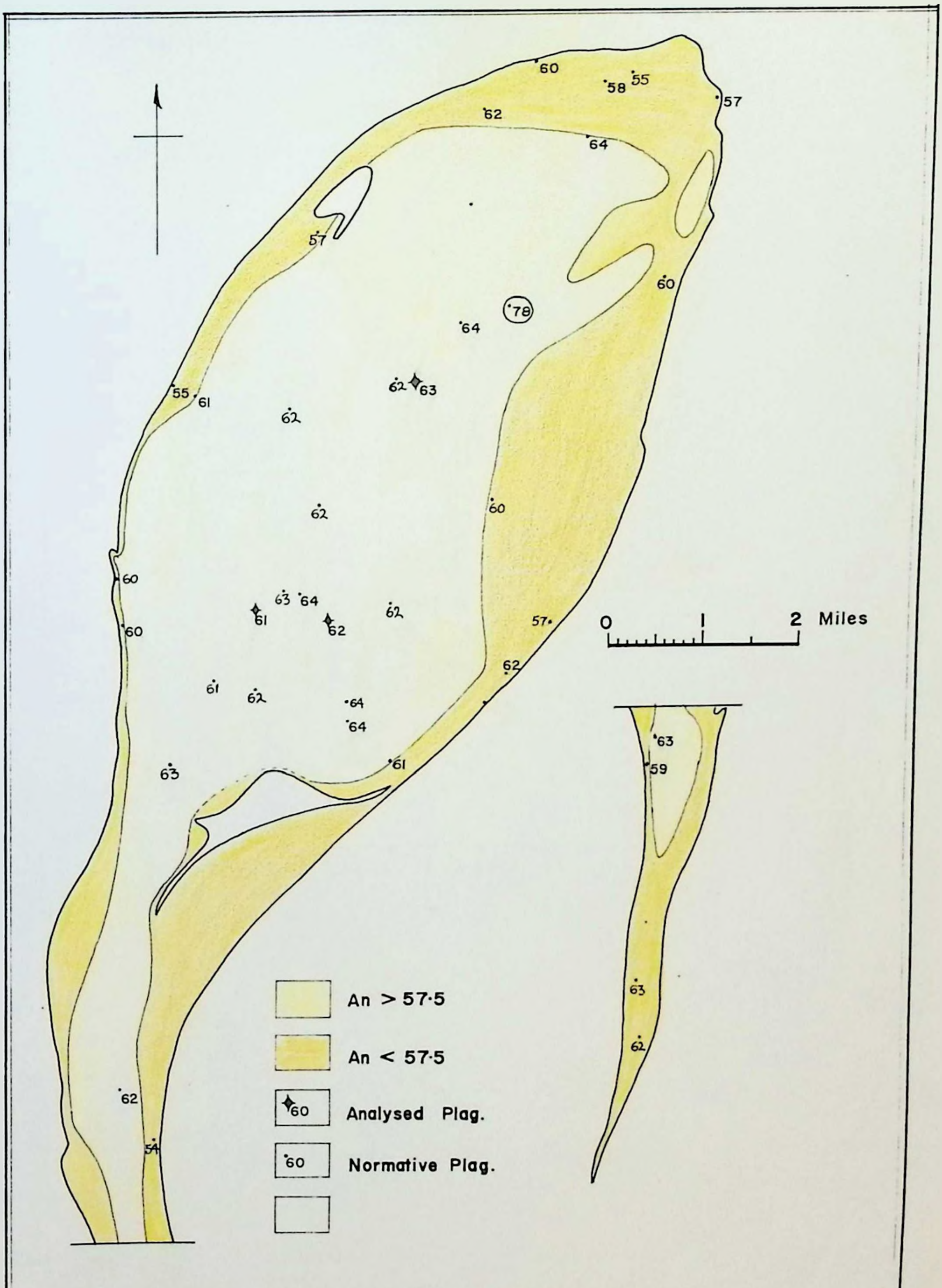
TABLE 5-2

Comparison of Optical and Micro-probe Data for Plagioclases

Lab No	Composition in An %	
	Michel-Lévy	Micro-probe
129	55	61
138	45	51
139	54	55
176	58	67
177	58	55
178	60	83
206	48	48
225	59	66
228	60	59
232	60	60
236	65	65
238	58	61
326	57	65
330	51	51
354	60	50



Notes:
1) In general, and especially when twinning is poorly developed (usually as a result of strain and flexuring), the optical method will tend to underestimate the An %. Note that points outside 5% limit all indicate optic An % are low.
2) Microprobe An % is based on Ca determination only. Significance of these values could have been improved by measuring another structurally significant element e.g. Al or Na.
3) Microprobe analyses from Haughton (1967).



MODAL An CONTENT of PLAGIOCLASE

Fig. 5-2

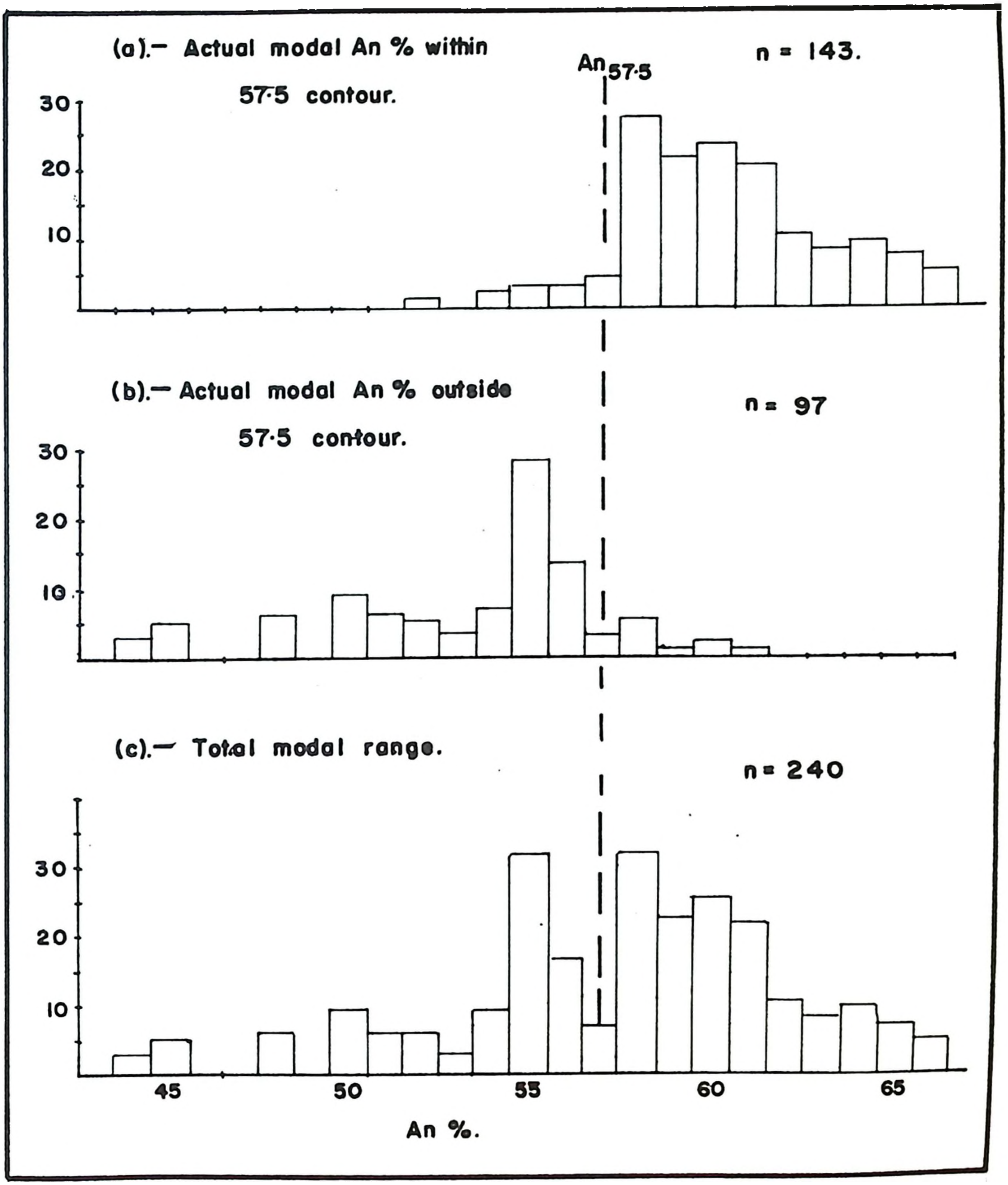


FIG. — 5-3 Histograms of optically determined An %.

there is surprisingly little regular change in An content over the body. Within the large central area, averaging An_{61}, no regularity to the variation can be discerned and much of it may be due to analytical error. The marginal area, averaging An_{53} but with modal value of An_{55}, appears to be significantly different. However comparison of fig. 5-2 with figs. 5-10 and 11 and Map I demonstrates the coincidence of the garnet- and epidote- foliated facies with these lower values - note especially the correspondence of narrow western and broad north and eastern areas in both cases. It can be reasonably supposed then that the development of the CaO-bearing phases, garnet, epidote (+ scapolite and hornblende, see below) account for at least part of the difference in composition between the two areas. This would appear to be confirmed by the normative plagioclases of the 35 whole rock analyses given in Table 6-1 and plotted on fig. 5-2. It is noted that except for the rocks on the extreme margins there is indeed less variation between the central (averaging $An_{62.7}$)[1] and marginal (averaging $An_{60.3}$)[1] plagioclases. (The norm calculation ignores the presence of secondary minerals.)

The amazing uniformity of plagioclase composition found in the Whitestone anorthosite is consistent with the results of Isachsen and Moxham (1966) who spectrographically analysed plagioclases at regular intervals in two sections (528 and 372 metres) through the Adirondack anorthosite. In one they found a variation from $An_{44} \rightarrow An_{54} \rightarrow An_{44}$ upwards but no regular variation in the other which averaged An_{51} - c.f. composition of Whitestone feldspar. The Or content of both

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[1] Because modal pyroxene contains up to 5% Al_2O_3 while in the norm calculation all Al is assigned to plagioclase, the normative plagioclase will be a few % higher in An than the modal value.

the Adirondack and Whitestone anorthosite is again remarkably constant - in the Whitestone it varies little from Or_3 (cf. Table 6-1) and in the Adirondack plagioclases it varies from Or_{4-7}.

Attention is drawn to the abnormally calcium-rich plagioclase in specimens 106 and 107 (107 is circled in fig. 5-2). These rocks are part of a strongly banded sequence identical to that of Plates 2-10 and 11, and it is noted that both the porphyritic type (107) and the inter-banded glomeropoikilitic type (106) are equally high[1]. On the other hand, specimen No. 283 = An_{61} is also part of a banded sequence. The reason for such high values in these two cases is not clear, but abundant optical and chemical data show that such values are extremely rare in this body.

A signal feature of this, and apparently many anorthosites, is the pervasive recrystallisation which has affected all primary phases to some degree. The textural relations of this phenomenon will be discussed in a later section. For the moment suffice it to say that there appears to be no appreciable chemical difference occasioned by the recrystallisation per se. In this study the primary and recrystallised types of plagioclase are optically identical. Buddington (1939, p.31) writes of rocks of the core of the Adirondack body (the so-called Marcy facies) ".... the variation between groundmass and large crystals in the same specimen was in no specimen greater than An_2." In the foliated, garnet and hornblende bearing, marginal Whiteface facies he notes that the groundmass feldspars were invariably about 5 mol% less calcic than the large primary crystals but that in both facies the primary crystals were essentially constant. This is consistent with the above discussion -

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[1] 107 = An_{78}; 106 = An_{77}

noting.the Whitestone anorthosite has no primary plagioclase in the marginal areas.

5b(iii) "Inclusions" in the Plagioclase

In common with the majority of massif-type anorthosites all the primary plagioclases contain orientated inclusions (cf. Buddington 1939, Wheeler 1955,60, Philpotts 1966 and other references therein). In the Whitestone the majority of these can be confidently identified as opaque needles a few microns wide and of variable length, strongly orientated parallel to (100) and (010) of the plagioclase. However, especially in the primary (i.e. non-recrystallised) plagioclase there also occasionally occurs somewhat larger silicate inclusions which are almost certainly amphibole; this phase has an identical orientation to the oxides. Although the presence of orientated inclusions in anorthositic plagioclases is widely recognised there is a minor controversy over their identity; they have been variously interpreted as pyroxene, hornblende, epidote, rutile, spinel, hematite and ilmenite (see discussion in Philpotts 1966, pp.24-25). It may be that some bodies contain only oxides whereas others contain only the silicate type thus accounting for some of the controversy. From a brief examination of a few thin sections it appears that the Adirondack and Morin anorthosite plagioclases are all much richer in oxides than the Whitestone. This correlates with the black primary feldspars of these bodies compared with the dark grey-blue of the Whitestone primary feldspars. On recrystallisation these inclusions are ejected so that in the three bodies such feldspars are white.

In an electron-probe study of <u>inclusion free</u> plagioclases from a variety of rock types Corlett and Ribbe (1967) show that plagioclase in the range An_{50-70} can contain up to 0.68% Fe and 0.06% Ti in solid solution: the respective values in Table 5-1 fall well within these values. Philpotts (1966) has argued that the orientated inclusions in the Morin are the result of exsolution of Fe and Ti - the work of Corlett and Ribbe would seem to indicate that plagioclase can contain an adequate amount of Fe and Ti to make this feasible. The possible significance of this exsolution is discussed in next section on pyroxenes.

5b(iv) Structural State of the Plagioclase

The parameters β and Γ defined by Smith and Gay (1958) which are held to be diagnostic of the structural state of the plagioclase, were calculated from X-ray diffraction traces, indexed using tables published by Bambauer et al. (1967). The results are presented in Table 5-1. Plotted on fig. 1 and 2 in Smith & Gay (1958), these plagioclases are inferred to be of low to intermediate structural state. This is in agreement with the findings of Philpotts (1966) for the Morin, and Romey (1967) for several assorted anorthosites.

5b(v) Scapolite in the Anorthosite

While common in various gneisses and skarns in the Grenville province (Shaw 1960, pt.I & II, Shaw et al 1963, pt.I & II) there is no significant literature associating scapolite with anorthosites. Table 5-3 lists noted occurrence of scapolite in anorthosite but none of them goes beyond recording its occurrence.

In the Whitestone body textural evidence that the scapolite is secondary after the plagioclase is both abundant and persuasive. In the general case the scapolite occurs as small crystals along plagioclase

TABLE 5-3

Scapolite in Anorthosites

Body	Amount	Reference
Adirondack	Averages 0.46 in Marcy facies(48) " 0.14 in Whiteface facies(100) However scapolite present in only $\frac{13}{155}$ specimens. Note: Apatite averages 0.18 and 0.20 in Marcy and Whiteface respectively but is present in $\frac{101}{155}$.	Crosby (1966) cf. also various modes in Buddington (1939)
S.E.Ontario	Range 1.15-7.25% in 4 specimens	Harrison (1944)
Kadavar (India)	Averages 0.8% in 5 specimens	Subramaniam (1956)
W.Greenland	Presence noted. No data.	Ellitsgaard-Rasmussen & Mouritzen (1954)
Whitestone	Range 0.1 → 41% Present in 85% of 360 specimens.	This work

interfaces and along fractures and cleavages in the plagioclase - see Plate 5-1. Where scapolitisation is more intense it may spread out, blot-like, to completely engulf several adjacent grains of plagioclase, and the scapolite then has the misleading appearance of being primary - such an interpretation has been favoured by Haughton (1967) - cf. his Plate 4.. However, it can be shown that towards the edges of such blots incomplete alteration of the plagioclase is found. It was noted that, in general, scapolitisation was more intense near mafic minerals than in plagioclase-rich domains in the same thin section and in most cases uralitisation preceded scapolitisation.

Of prime significance is the almost ubiquitous presence of haloes in the plagioclase immediately surrounding the scapolite.[1] The areas of such haloes are roughly proportional to the area of the related scapolite and in propitious sections plagioclase in the halo is seen to be 10% poorer in the An molecule than the remainder of the same grain. Such haloes may occur wholly in one grain, round scapolite in a fissure in that grain or, in the case of interfacial scapolite, the halo may occur in the several contingent grains.

Relevant to this Haughton (1967), in an electron probe study of plagioclase/scapolite pairs, discovered that the scapolite in the Whitestone anorthosite averaged Me_{75}[2] while the coexisting plagioclase averaged An_{61}. Comparing densities of plagioclase and scapolite[3] the following relations are noted:-

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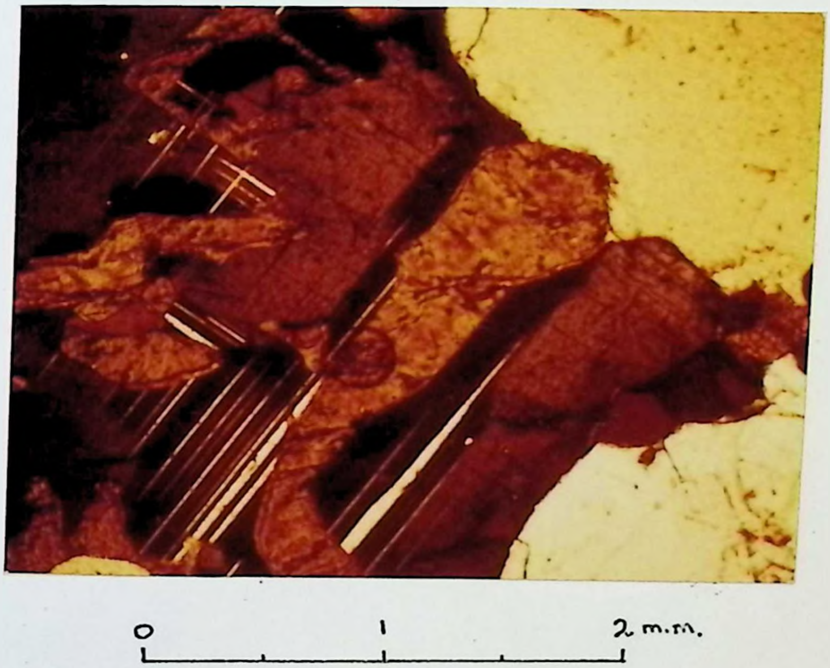
[1] On microprobe study this will undoubtedly prove to be invariable since its recognition optically depends on appropriately orientated sections.

[2] In this study only the Ca content of both the plagioclase and scapolite was determined - the compositions were calculated assuming stoichiometry (Haughton 1967).

[3] Plagioclase from Deer Howie & Zussman, scapolite from Haughton (1967). Considerable scatter is associated with latter values.



<u>Plate 5-1</u> Scapolite replacing plagioclase - nic.
Note halo in plagioclase round scapolite, shown by differing extinction positions.

Plag. An Composition	D	Composition of Scapolite of Equivalent density
An_{50}	2.68	Me_{60}
An_{60}	2.70	Me_{70}

Further, in neither interfacial nor fissure replacement was any evidence of volume change observed (note, expansion cracks are associated with serpentinisation of minor olivine in this body). Assuming, then, a volume for volume replacement and using figs. 5, 6, 7 and 8 in Haughton (1967) to estimate the approximate composition of a scapolite of Me_{75} and using plagioclase analysis 230, Table 5-1 (this thesis), the data presented in Table 5-4 is obtained. The data are recalculated assuming a standard cell of each mineral, containing 160 oxygens, represents an equal volume - see Barth 1948. I take this calculation to indicate the relative movement of cations during the reaction induced by the vapour pressure of the fluid phase and that total reaction is, excepting introduced volatiles, essentially isochemical. Note that in highly scapolitised rocks (i.e. where scap x 100/scap + plag $>$ 50%) the process will result in a lowering of the <u>modal</u> An but not the <u>normative</u> An content. Compare fig. 5-4 and fig. 5-5.

According to Haughton's correlation diagrams a Me_{75} scapolite would have volatiles in the ratio $CO_2:SO_3:Cl = 3:2:0.2$. Table A-7 lists 7 analyses including volatiles and in these the volatiles average $CO_2:SO_3:Cl$ = 10:2:0.4. Assuming the vast majority of the volatiles are in the scapolite[1] it appears that anorthositic scapolites of composition Me_{75} have a

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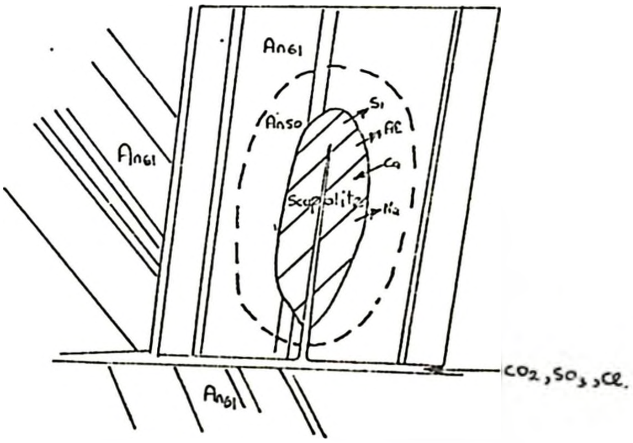
[1] Hornblende, the only other hydrous phase, contains only 0.02% CO_2. Table 5-7.

TABLE 5-4

Data on Plagioclase-Scapolite Reaction

(a) Composition, Wt.%			(b) Standard cell on basis of 160 oxygens			(c) Cations involved in transformation of $An_{61} \rightarrow Me_{75}$ of equal volume		
	Me_{75}	An_{61}		Me_{75}	An_{61}		Added	Subtracted
SiO_2	45.2	52.6	Si	41.63	47.89	Si	...	6.26
Al_2O_3	27.7	30.2	Al	30.06	32.41	Al	...	2.35
CaO	17.5	12.0	Ca	17.26	11.70	Ca	5.56	...
Na_2O	2.6	4.1	Na	4.63	7.22	Na	...	2.59
K_2O	0.5	0.5	K	0.59	0.58	K	0.01	...
CO_2	3.2	–	C	4.02	–	C	4.02	...
SO_3	1.8	–	S	1.24	–	S	1.24	...
Total	98.5	99.4	Total	99.43	99.80	Total cation	10.83	11.20
						Total valencies	34.7	34.7

(d) % change in cations relative to An_{61} (ignoring volatiles)		
	$An_{61} \rightarrow Me_{75}$	$An_{61} \rightarrow An_{50}$
Si	-13.1%	4.8%
Al	- 7.2%	2.5%
Ca	47.5%	-16.2%
Na	-35.9%	34.7%
K	1.7%	----



Notes: Values in table (d) have the correct sign to be consistent with an essentially isochemical change (excluding volatiles). Discrepancy in magnitudes probably due to inherent assumptions, which are:-

1) Value of Me_{75} (average for body) is valid for specific scapolite altering from plagioclase of composition of No.230 (An_{61}).
2) Composition of Me_{75} used, extrapolated from Haughton's data, is appropriate.
3) Plagioclase in halo is all one composition, i.e. there is no compositional gradient.

higher CO_2/SO_3 ratio than those used in erecting Haughton's diagrams; those used by him were mainly from skarns and scapolite-calcite-pyroxene gneisses. Considering the amount of calcite in these latter this inference is rather puzzling.

The volatile content of the scapolite is presumably a function of that of the percolating fluid phase and it is significant to note from Table 5-5 that there appears to be a significant difference in the fugacities of the volatile components among anorthosites and this is reflected in the "accessory" minerals.

TABLE 5-5

$\frac{P_2O_5}{CO_2}$ ratio in Anorthosites

Anorthosite	Nos. of samples	CO_2%	P_2O_5%	$\frac{P_2O_5}{CO_2}$x10	Reference	Notes
Whitestone	7	0.5	0.04	0.8	This work	Scap. ≫ Apatite (Table B-1)
Adirondack	7	0.4	0.13	3.25	Buddington(1939)	Apatite > Scap. (Table 5-3)
Roseland Va.	6	0.09	0.20	22.0	Herz(1966)	Extremely rich in apatite, no scapolite[1]

The distribution and abundance of scapolite in the Whitestone body is summarised in fig. 5-4. In the marginal areas (i.e. >5%) the scapolite ratio varies irregularly with respect to contacts, in the range 5-50%.

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[1] See also Philpotts (1967).

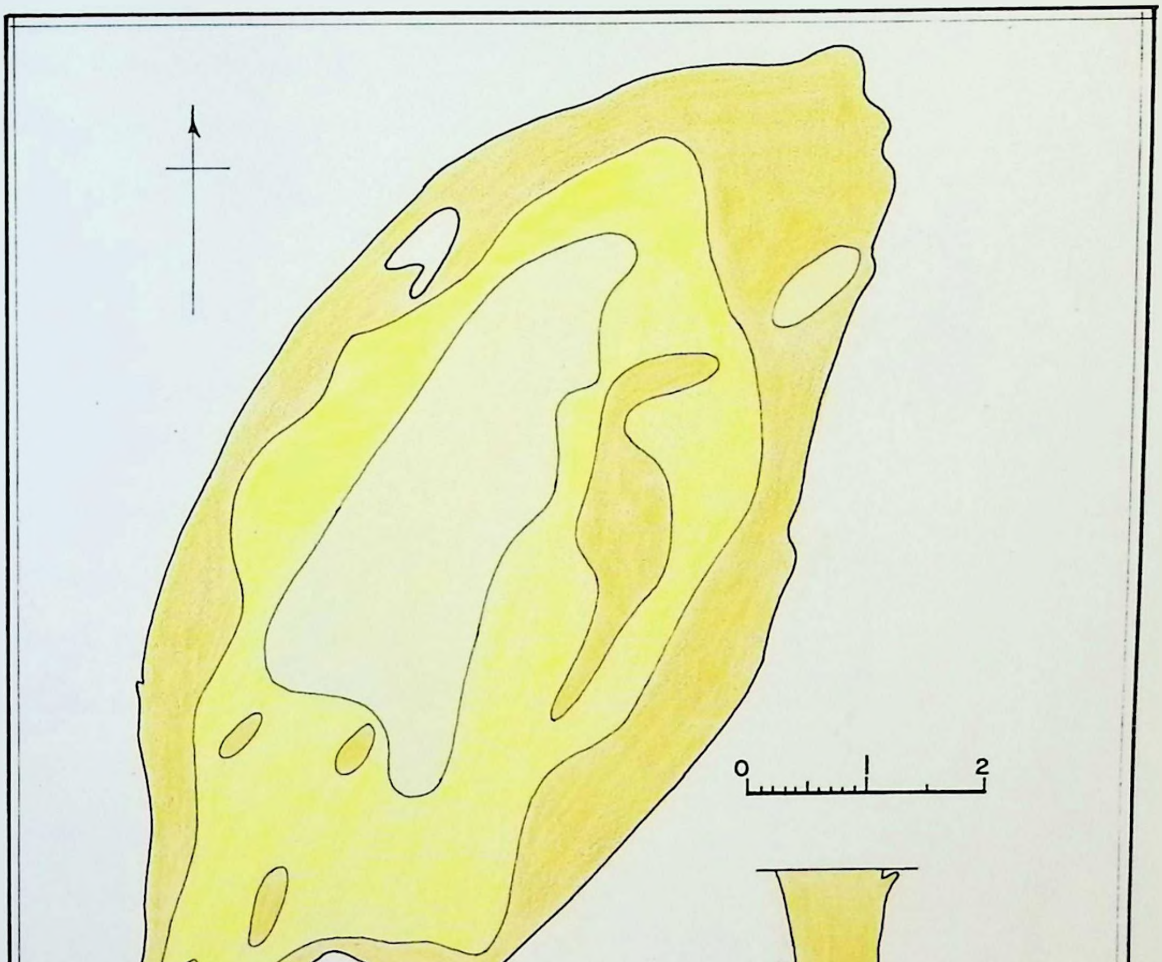
0
1
2
Ratio > 5%
" 1-5%
" < 1%
MODAL RATIO $\frac{\text{Scapolite X 100}}{\text{Scapolite + Plag.}}$ DISTRIBUTION

Fig. 5-4

While some of this variation may be due to imprecision of the point-counting, undoubtedly the larger part can be attributed to the irregular and local development of conditions favourable to the movement of the fluid phase.

Textural evidence to be introduced in a later section indicates that scapolitisation occurred after initial crystallisation of the plagioclase but prior to the recrystallisation: the time interval between these two events is inferred to be relatively short. From this it is deduced that the fluid phase responsible for the development of scapolite was a product of the differentiation of the magma and not of a later event. It is noted that scapolitisation of the plagioclase stops abruptly at the edge of the anorthosite; in the country rocks only some impure marbles carry scapolite. It is not clear why the fluid phase which so successfully imposed a Fe-metasomatism on the surrounding rocks failed to also produce scapolite. It may be that the fluid phase changed composition before reaching the country rocks, or perhaps a lower temperature prohibited reaction.

5c. Pyroxene-Amphibole

In this body the main, primary mafic-phase is a green to pale-green clinopyroxene which occurs, in trace amounts at least, in virtually all rocks. In most specimens it is altered to some degree to a dark-green amphibole which may, especially towards the margins, completely replace the pyroxene. Five pyroxenes were separated for analyses at an early stage of the study: these are given in Table 5-6 along with three

TABLE 5-6

Analyses of Clinopyroxenes

Lab No	52	90	107	278	282	A.	B.	C.
SiO_2	48.79	50.00	49.27	48.71	47.98	50.13	49.96	45.80
TiO_2	0.68	0.49	0.78	0.83	0.84	0.58	0.67	1.42
Al_2O_3	5.76	4.75	5.97	5.90	6.74	4.71	4.30	7.06
Fe_2O_3	3.51	2.42	2.55	2.88	3.56	2.67	1.96	3.14
FeO	8.05	8.02	7.35	8.68	8.55	9.66	8.87	10.29
MnO	0.23	0.08	0.18	0.23	0.21	0.23	0.22	0.20
MgO	10.61	11.49	11.29	10.41	9.84	10.98	12.00	8.42
CaO	21.57	21.48	22.08	21.74	21.71	19.54	20.43	21.58
Na_2O	0.79	0.86	0.69	0.79	0.77	0.81	0.52	0.68
K_2O	0.01	0.03	0.04	0.03	0.13	0.14	0.00	0.01
Cr_2O_3	0.05	0.00	0.03	0.02	Tr	nd	nd	nd
Total	100.05	99.62	100.23	100.22	100.33	99.45	98.93	98.80

Structural Formulae on Basis of 6 Oxygens

Lab No	52	90	107	278	282	A.	B.	C.
Ca	0.87	0.86	0.88	0.88	0.87	0.79	0.83	0.86
Mg	0.60	0.65	0.63	0.59	0.56	0.63	0.68	0.47
Fe^{+2}	0.25	0.25	0.23	0.27	0.27	0.30	0.28	0.32
Mn	0.01	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Fe^{+3}	0.10	0.07	0.07	0.08	0.10	0.08	0.06	0.09
Al	0.10	0.09	0.11	0.09	0.11	0.10	0.08	0.13
Ti	0.02	0.01	0.02	0.02	0.05	0.02	0.02	0.04
Na	0.06	0.06	0.05	0.06	0.06	0.07	0.04	0.05
Si	1.84	1.88	1.84	1.83	1.81	1.89	1.89	1.82
Al	0.16	0.12	0.16	0.17	0.19	0.11	0.11	0.18
X + Y	2.01	1.99	2.00	2.00	2.03	2.00	2.00	1.97
Ca%	47.5	47.0	48.4	48.1	48.1	43.6	44.6	49.1
Mg%	32.8	35.5	34.6	32.2	30.9	34.8	36.6	26.9
Fe%	19.7	17.5	17.0	19.7	21.0	21.6	18.8	24.0

$\frac{Fe}{Fe + Mg}$ for whole rock

-	61.2	31.5	-	-	53.4	37.4	46.8

TABLE 5-6 (Continued)

Lab No	52	90	107	278	282	A.	B.	C.
Pyroxenes recalculated as end members[1]								
Acmite	6	6	5	6	6	7	4	5
Jadeite	0	0	0	0	0	0	0	0
Tschermak	16	12	16	17	19	11	11	18
Hedenbergite	25	26	24	28	27	31	29	34
Diopside	53	56	55	49	48	48	54	43
Enstatite	-	-	-	-	-	3	2	0

52 (Field No L1-291)

Pale-green, non-pleochroic clinopyroxene from glomeropoikilitic gabbroic anorthosite. Very little uralitisation. Glomeropoikilitic texture well preserved and pyroxene is optically continuous over large areas, recrystallisation is minor. No evidence of exsolution of either oxide or silicate phase: i.e. there is no reason to suppose analysis varies much from primary composition.

Analyst J. Muysson, McMaster

90 (Field No L0-67)

Green, slightly pleochroic clinopyroxene from strongly foliated, garnetiferous, gabbroic anorthosite. Very little uralitisation but pyroxene is completely recrystallised. No exsolved phases. Pleochroic scheme - green : pale greeny brown : green (i.e. best seen in cross-section).

Analyst J. Muysson, McMaster

107 (Field No L1-127)

Pale-green, slightly pleochroic clinopyroxene from mafic part of a strongly banded sequence (similar to Plate 2-). Although plagioclase is highly scapolitised there is only minor uralitisation. Most of pyroxene is recrystallised and homogeneous but a few larger crystals contain trains of small (0.05 x 0.03 mm) blocks of a colourless silicate phase parallel to (110). Such crystals also contain a few small globules of sphene. It may be that exsolved silicate phase is rutile (cf. Moore 1968).

Analyst J. Muysson, McMaster

TABLE 5-6 (Continued)

278 (Field No L1-81)

Pale-green, slightly pleochroic clinopyroxene from porphyritic-facies gabbroic anorthosite. Uralitisation minor. Again most of clinopyroxene is recrystallised and homogeneous but non-recrystallised grains contain both an exsolved oxide phase and a colourless silicate phase. Oxide phase is at 45° to cleavage in cross-section i.e. parallel to (100) and (010) but trapezoidal shape in longitudinal section suggests they may be orientated in some direction within these planes. These oxides occur as small (0.05 x 0.03 mm) blocks of rather irregular distribution but they tend to be concentrated in cores. They are assumed to be hemo-ilmenite (see text). Colourless silicate phase on other hand is concentrated on margin of crystal of similar size to oxides.

Analyst J. Muysson, McMaster

282 (Field No L1-85)

Pale-green, slightly pleochroic clinopyroxene from glomeropoikilitic anorthosite adjacent to 278. Very little uralitisation. Completely recrystallised. No exsolution; however, pyroxene does contain rare blebs of sphene which in a few cases appear to be elongated but these are rare and such elongation may be fortuitous.

Analyst J. Muysson, McMaster

A. Augite from Marcy type anorthosite, Adirondack anorthosite.
Analysts R.B. Ellestad & L.C. Peck - given in Buddington (1950). Table 1 No.1 p.660.

B. Augite from anorthositic gabbro, Adirondack anorthosite.
Analyst R.B. Ellestad - given in Buddington (1950). Table 1 No.2 p.660.

C. Salite from gabbroic anorthosite gneiss, Adirondack.
Analyst R.B. Ellestad - given in Buddington (1950). Table 1 No.3 p.660.

Note 1) A, B and C contain the surprisingly high values of 0.91, 0.64 and 0.30 wt% H_2O respectively.

2) Pyroxene end members calculated according to scheme of Yagi (1953), as given in Yoder & Tilley (1962) p.366-7, with modification as proposed by White (1964).

clinopyroxenes from the Adirondack anorthosite for comparison[1]. In some anorthosites - e.g. Morin (Papezik 1964, Philpotts 1966) and the St. Urbain (Mawdsley 1927) - it appears that orthopyroxene is the main mafic although clinopyroxene is usually also present. It will be shown in this section that in the Whitestone pluton the orthopyroxene is not of primary origin.

5c(i) Recrystallisation and Exsolution in the Pyroxene

As is obvious petrographically, the pyroxenes have not escaped unscathed from the recrystallisation any more than the plagioclase. Plate 5-3 illustrates the development of this recrystallisation as it affects the pyroxenes.

The recrystallised pyroxene is green, slightly pleochroic in green and greeny-brown, with a strong basal parting. It occurs in 3-5 mm. anhedral grains and, when an entire, large, primary grain is affected, they occur as a mosaic of equidimensional grains which retain the typical, poikilitic, straight-edge relation vis-á-vis the plagioclase, which may also be completely recrystallised. Contrasting with the primary grains they are homogeneous and do not contain any orientated inclusions although they may contain a few, irregular, random blebs of oxide or sphene - see below. The recrystallisation is estimated to be about 80% effective,

---

[1] At an early stage it seemed necessary to examine pyroxenes from the several contrasted facies in the anorthosite (glomeropoikilitic etc.) to corroborate that they are indeed genetically related and this, together with a desire to choose pyroxenes as little uralitised as possible, governed the selection of 5 given. Further analyses from other parts of the body were intended but, for various reasons, this proved unrealistic. Distribution of the five pyroxenes are biased towards eastern part of anorthosite.

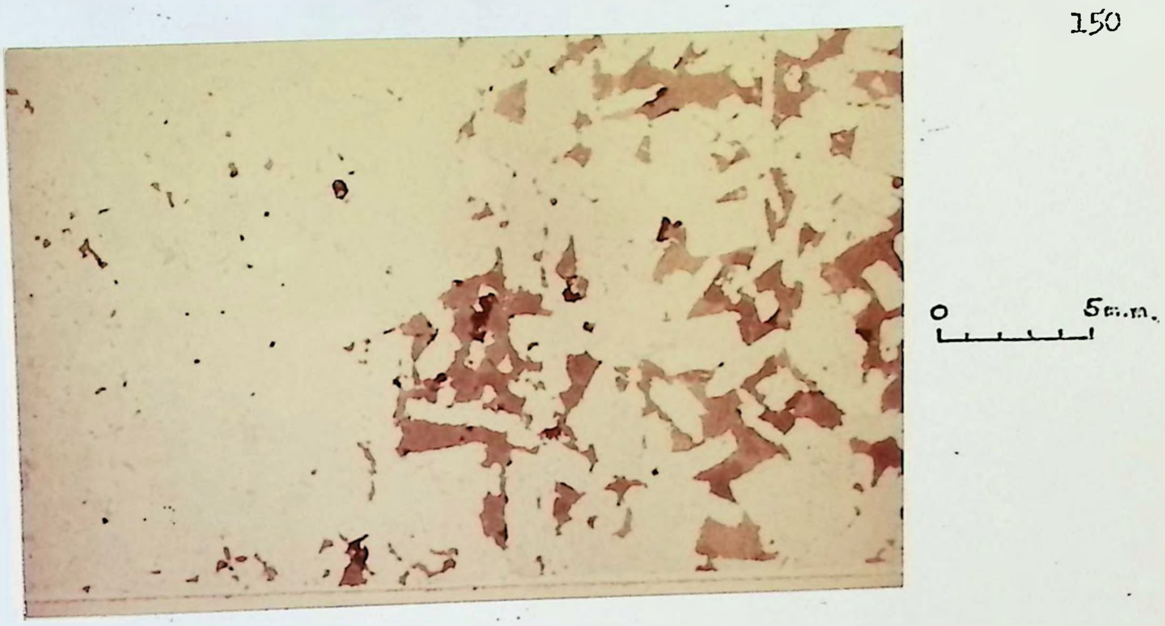

Plate 5-2 Glomerophenocryst of clinopyroxene - plane.
Note well developed plagioclase laths - however, under crossed nicols each of these laths is seen to be now composed of several different grains of plagioclase due to subsequent recrystallisation.

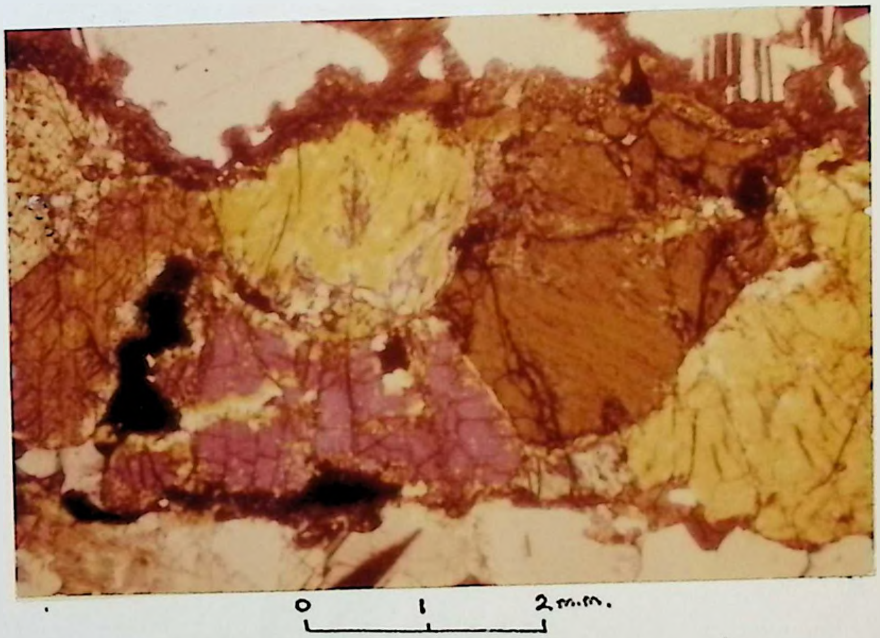

Plate 5-3 Recrystallisation of pyroxene - nic.
Here note that under cross nicols clinopyroxene is also recrystallised to a mosaic of small homogeneous grains retaining, although somewhat blurred, the original straight edges shown in 5-2.
Note that narrow rim of amphibole and quartz occurs only on these primary grain boundaries and does not occur at post-recrystallisation interfaces.

ranging from 100% on the margins to 50% in the core.

The primary pyroxene occurs as large green, poikilitic grains up to 30 mm. (and probably larger than the slide) characterised by orientated inclusions of a) oxides, and b) a colourless silicate phase.

The oxides occur, in general[1], as rectangular plates, averaging 70 x 30µ, orientated parallel to (100) and (010), and they are interpreted as being an exsolved phase rather than epitaxial or included material for the following reasons:-

1) Strong orientation (see Plate 5-4); in appropriate sections all the oxides in a grain have trapezoidal shape suggesting that the rectangular plates are also rationally elongated within the planes (100) and (010).
2) Oxide is lacking as a primary phase in the vast majority of rocks whose pyroxenes exhibit this feature.

In general, possibly because of uralitisation (see below), the oxides are absent in the marginal portions of the grain.

The second type is more problematical, occurring as trains of colourless blebs (30 x 10µ), with higher birefringence and R.I. than the host clinopyroxene, which are orientated perfectly parallel to the (110) pyroxene cleavage. Both on the basis of birefringence and orientation they are unlikely to prove to be an orthopyroxene; possibly they are rutile (see Moore 1968) but final identification must await a microprobe analysis. This type of exsolution is both rarer than and, in general,

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[1] In one case the oxide occurred as a very fine dust estimated to be of the order of 1µ, in which no orientation could be confirmed.

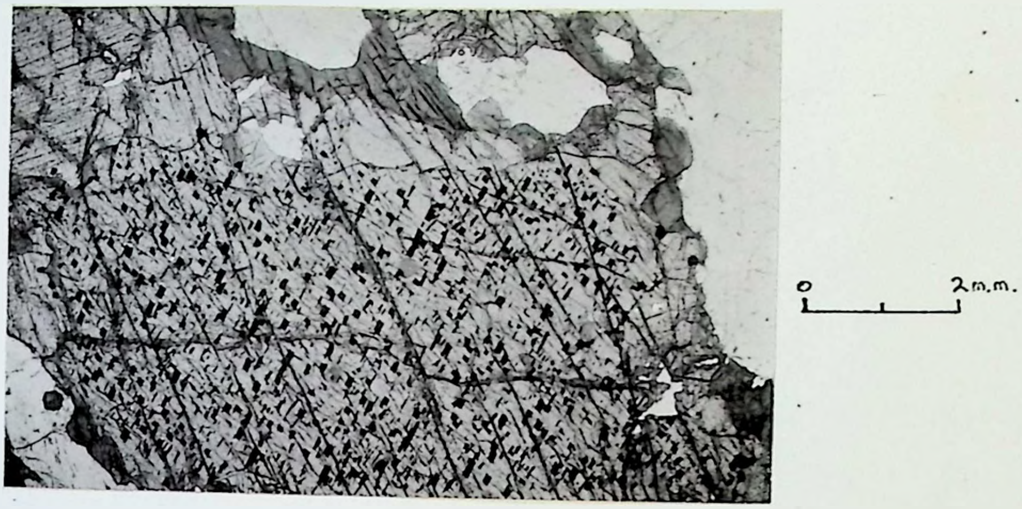

Plate 5-4 Oxide exsolution in clinopyroxene - plane. Note here that oxides are restricted to large central unrecrystallised portion. Rimming this is area of small, recrystallised grains free of oxides - light gray area; this is, in turn, rimmed by amphibole - dark gray. Although section is such that pyroxene cleavage is not at 90°, note that orientation of oxides is at 45 to cleavage.

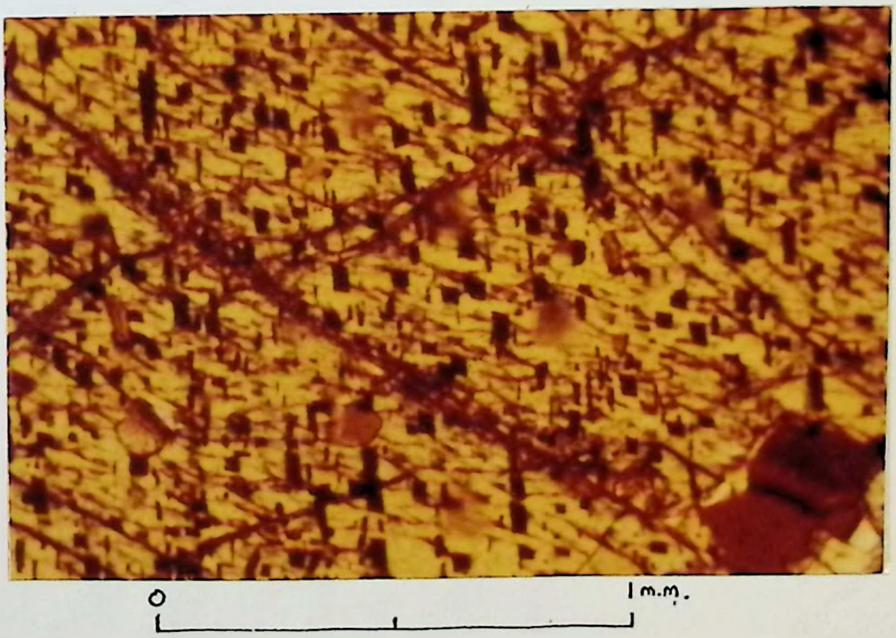

Plate 5-5 Same slide as 5-4 at higher magnification - plane.

mutually exclusive with the oxide type. Plate 5-6 and -7.

At this point I introduce an enigmatic rock found near the N.W. nose of the pluton just N. of the Whitestone River[1] - locality 25, Map 2a. The outcrop is relatively small, probably less than 50 yds. square, but appears too large to be an erratic. It is a very dense, black, rusty-weathering rock composed almost entirely of pink-green pleochroic orthopyroxene with minor interstitial plagioclase. The orthopyroxene shows a complex exsolution of clinopyroxene in at least two directions - see Plate 5-8 and compare with Plate 1-D, Boyd & Brown (1968). As far as I am aware this is the first recorded instance of an ultramafic rock being 'associated' with a massif type anorthosite. Unfortunately, since the contact of this rock with the surrounding anorthosite is nowhere exposed it is not possible to gauge the strength of this association. In any event, the exsolution in these pyroxenes is radically different from that in the anorthosite proper, although it is significant to note that what appears to be rare grains of primary clinopyroxene in specimen 25 also contain orientated oxide exsolution!!

One of the effects of the recrystallisation is the ejection of both the oxide and silicate exsolution from the pyroxene. The rare, irregular blebs of oxide or sphene noted in the recrystallised types are interpreted in this way. Further, Philpotts has recognised an identical recrystallisation in the Morin rocks and, because of much coarser grain size and less extreme recrystallisation, he has been able to separate and analyse a primary and recrystallised pyroxene from the same rock (Philpotts 1966, Table 2): his data indicate that the essential difference between the two (expressed as cation % relative to the igneous pyroxene) is:-

a) Loss of 60% and 32% in Ti and Fe^{2+}

b) Gain of 114% in Fe^{3+}

---

[1] This rock was discovered during my last field season and, unfortunately, was misinterpreted as an inclusion of metasomatised pyroxene-rich gneiss similar to specimen 454; such inclusions are common in this area. It is introduced at this point rather than in chapter 2 to emphasise that although its possible implication is alarming, its genetic relation to the anorthosite has not been proved.

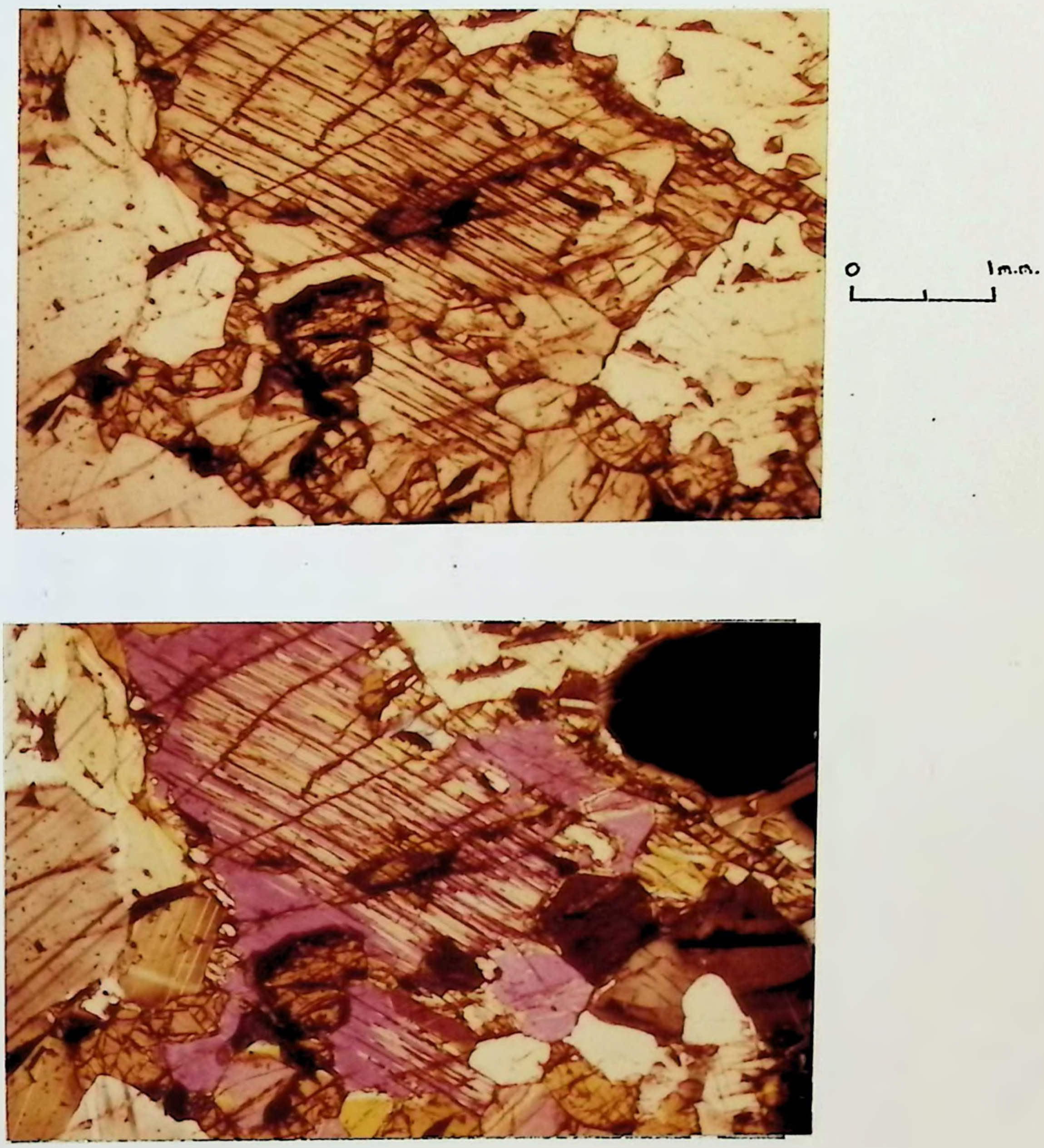

Plate 5-6 and -7 Clinopyroxene showing
(a) silicate exsolution parallel to pyroxene cleavage
(b) rim of secondary orthopyroxene
(c) halo in plagioclase abutting on orthopyroxene best seen in upper right corner of 5-7.

Note that this clinopyroxene is part of a larger glomerophenocryst and that orthopyroxene is not restricted only to outside of this large primary crystal, as would be expected if orthopyroxene was primary, but in fact it occurs at virtually all pyroxene/plagioclase interfaces.

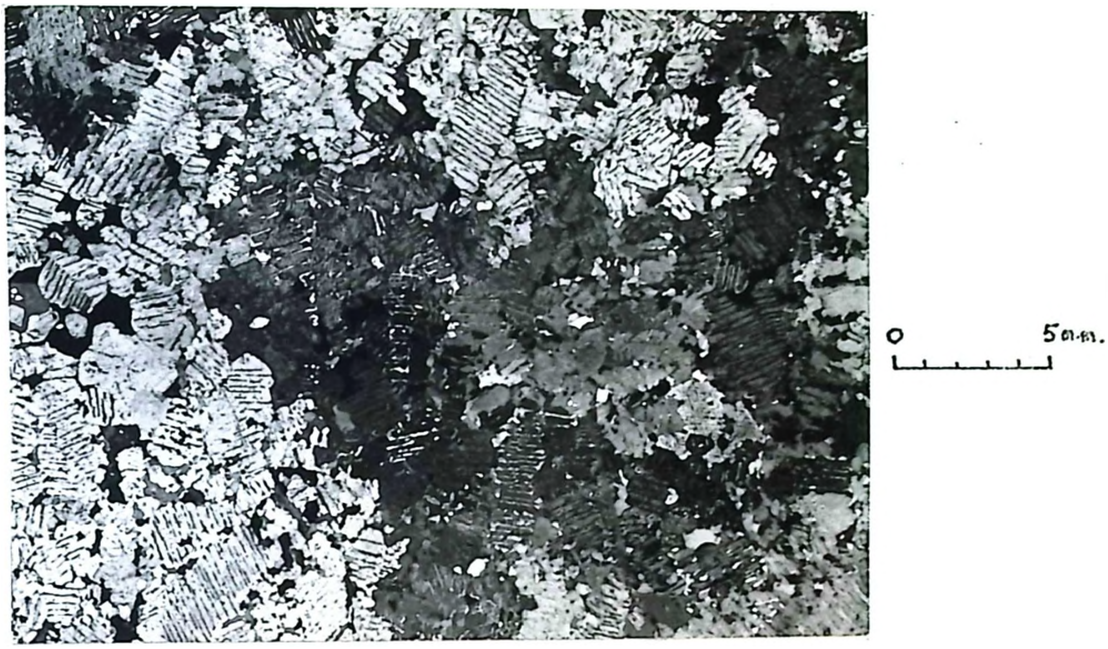

Plate 5-8 Orthopyroxene with abundant exsolution of clinopyroxene from locality 25.

c) Changes in Si, Mg and Ca are minor (-3, -3, + 2% respectively) and are probably within limits of analytical error. Loss of 13% in Al may also, although less certainly, be similarly interpreted.

To account for this pyroxene analyses of Table 5-6[1] are plotted on fig.6- as triangles.

5c(ii) Note on Oxide Exsolution in Clinopyroxene

A literature survey of recent papers dealing specifically with the optical, chemical and physical properties from a variety of rocks indicates that while included phases occur frequently, oxide as an exsolved phase is rare. See e.g. Wager & Deer (1939), Muir (1951), Brown (1957,1963), Wilkinson (1957,1966), McDougall (1961), Aoki (1964), Muir & Long (1965), Huckenholtz (1966), Lewis (1967) and Aoki & Kushiro (1968). It is assumed that such specific papers would at least note the presence of orientated oxides. The lack of such features in pyroxenes of alkaline affinities which may contain up to 2.09% TiO_2 and 6.94% Fe_2O_3 is particularly noteworthy.

On the other hand, Philpotts (1966) notes the presence of oxide plates in the Morin clinopyroxenes but does not comment on their origin or significance. Deer & Abbot (1965) note oxide needles in (010) and (100) in the Kap Edvard Holm clinopyroxenes and suggest they result from exsolution consequent on falling temperature and increasing water vapour

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[1] Which variously represent completely primary, completely recrystallised and bulk analyses of the two - see notes on Table 5-6.

pressure[1]. Best & Mercy (1967) in discussing the mafic minerals of the Guadaloupe Igneous complex note "…. specks and patches of ilmenite and magnetite within olivines and pyroxenes (which) seem related to post-crystallisation exsolution."[2] Although not referring to this exsolution in particular, Best proposes that many features of this complex seem attributable to slow cooling in the presence of an intergranular aqueous phase.

On theoretical grounds Verhoogen (1962) argues that Ti is only likely to enter the pyroxene structure at relatively high temperatures; that is, it is a thermodynamic misfit at lower temperatures, and Moore (1968) argues that pyroxenes crystallised under high pressure are not likely to tolerate the distortion due to "foreign" atoms at lower temperatures and pressures and, on this basis, explains the rutile exsolution in orthopyroxene from the Gosse Pile ultramafics. While pressure may possible be a contributory factor in the case of the anorthosite there is no evidence from their mise-en-place that such is the case for the Kap Edvard and Guadaloupe rocks. I propose that extravagantly slow cooling, perhaps aided and abetted by a fluid phase, is a very important factor in the exsolution.[3] A slow cooling is consistent with both the large, unzoned plagioclases and pyroxenes; further, an unusually slow cooling is deduced from the recrystallisation features to be discussed in section 5f.

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[1] Preliminary microprobe data indicated they consist of Fe and Ti. On the basis of one polished section the oxide phase in the Whitestone anorthosite is tentatively interpreted as a homogeneous hemo-ilmenite s.s.

[2] The orientated nature of these oxides can be seen in their figure 2 although they do not note it in the text.

[3] Bown (1960) confirmed by X-ray the 100 and 010 orientation of oxides in several unidentified pyroxenes. He suggests such exsolution is due to reheating. I suggest abnormally slow cooling is equivalent to reheating.

5c(iii) Orthopyroxene-Clinopyroxene Relations

In chapter 2 the problem of the Green Feldspar Facies (G.F.F.) was introduced and it was concluded that the diagnostic features of this spatially restricted facies (veins in the feldspar, orthopyroxene rims on the clinopyroxene, and the garnet coronas) were a) cogenetic and b) secondary. Fig. 5-5 illustrates the restriction of orthopyroxene to rocks defined in the field as being G.F.F. The presence of orthopyroxene itself is not readily identifiable in hand specimen. Further, it should be obvious by now that I consider an Fe- and Ti-rich fluid phase[1] as a major factor in rationalising many petrological phenomena connected with the anorthosite but while it is relatively easy to intuitively relate the ramifying iron-rich veins in the feldspar (see chapter 2, p.50) to this fluid the origin of the orthopyroxene and garnet are not quite so obvious.

The orthopyroxene itself is strongly pleochroic in bright green and pinky-red, with $2v_x = 63^\circ$ and $n_z = 1.696$. From fig. 10, Deer Howie & Zussman, Vol.2, these properties indicate a composition of $En_{70} \pm 3$ mol%, but this can only be regarded as tentative until a chemical analysis is available.

In practically all thin sections of this facies that the orthopyroxene rims the clinopyroxene is abundantly clear - Plate 5-6 and 5-7. Indicating that the rim is secondary is the observation that commonly[2] the areas of plagioclase grains abutting on the orthopyroxene rim show a notable enrichment in the An molecule - such haloes indicating a repositary

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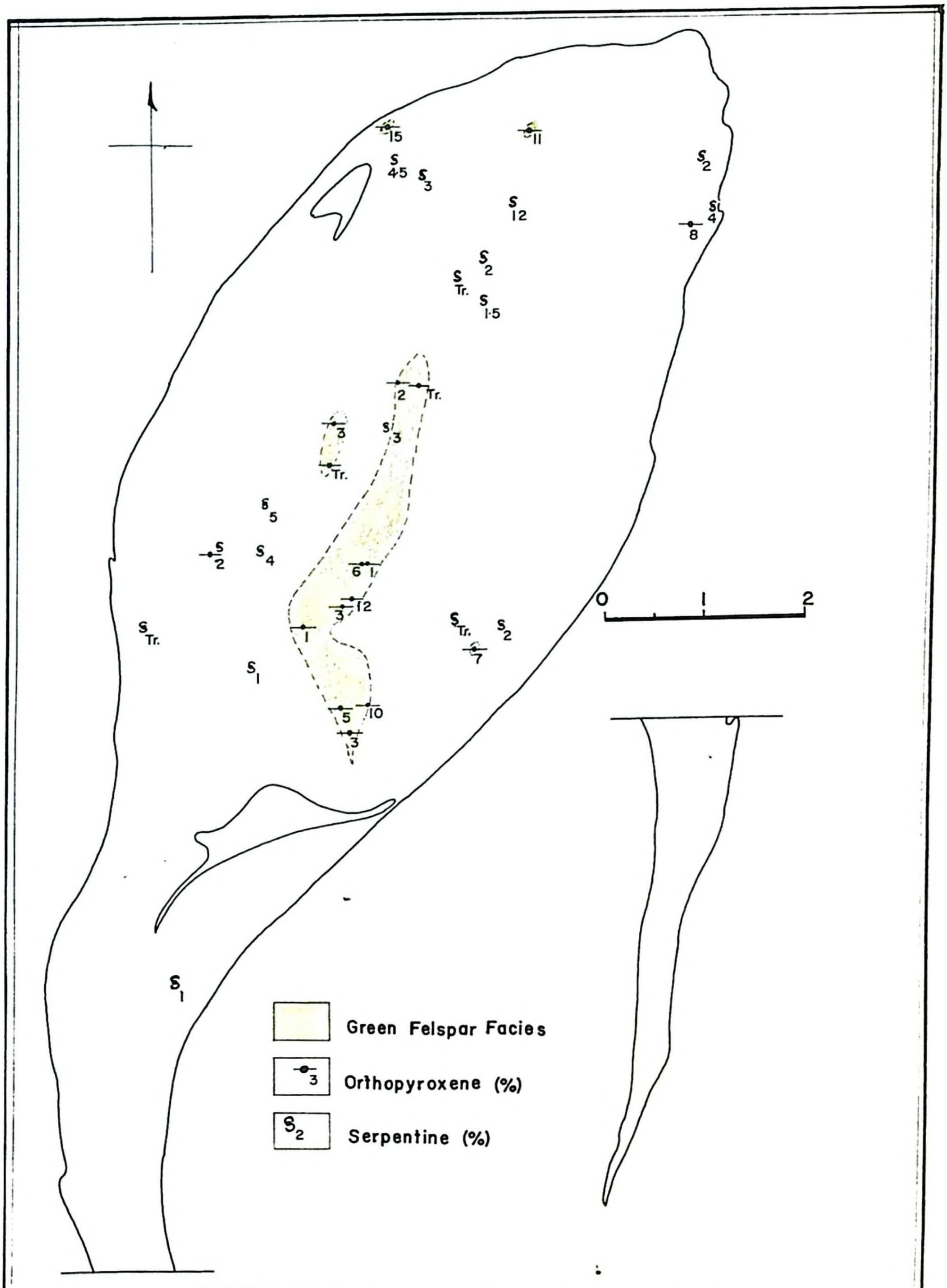
[1] The development of this fluid phase will be discussed in a later section.

[2] Very probably invariably, when examined by electron micrope; petrographic evidence depends on presence of suitably orientated and twinned plagioclase.



DISTRIBUTION OF MODAL ORTHOPYROXENE & SERPENTINE

Fig. 5-5

for the Ca-ion redundant in the transformation to orthopyroxene. In a discussion of the chemistry of the pyroxenes it will be shown that the anorthositic clinopyroxene is neither of the type that crystallises with a Ca-poor pyroxene nor of the type that might be expected to show exsolution of such a phase. Moreover it is noted that in glomeroporphyritic G.F.F. rocks the orthopyroxene is not restricted to the outside of the glomerule as would be expected if it crystallised at a late stage from the intercumulus liquid but in fact occurs at most pyroxene/plagioclase interfaces, indicating it formed simultaneous with (or post) the recrystallisation of the initially large igneous pyroxene, see Plate 5-7. Significant also is the fact that the G.F.F. rocks are unique among rocks of the core of the anorthosite in having oxide as a (minor) phase in the matrix of the rock; usually such oxides have a rim of orthopyroxene.

The occurrence of chains of sub-hedral garnet rimming and mimicking such pyroxenes as illustrated in Plate 5-9 , and the complete restriction of garnet in such a singular habit to this rock-type leaves little room to doubt that the development of orthopyroxene and garnet is intimately related. A garnet chain as completely developed as in Plate 5-9 is rather rare, occurring only where the clinopyroxene is completely altered to orthopyroxene.

Lacking adequate analytical data interpretation of such phenomena leaves something to be desired but even on petrographic evidence alone it is clear that the orthopyroxene and garnet feature of the G.F.F. rocks are more conveniently considered in terms of 'metamorphic' rather than igneous processes. In fact I believe they are due to the same general conditions that resulted in the recrystallisation of the igneous phases

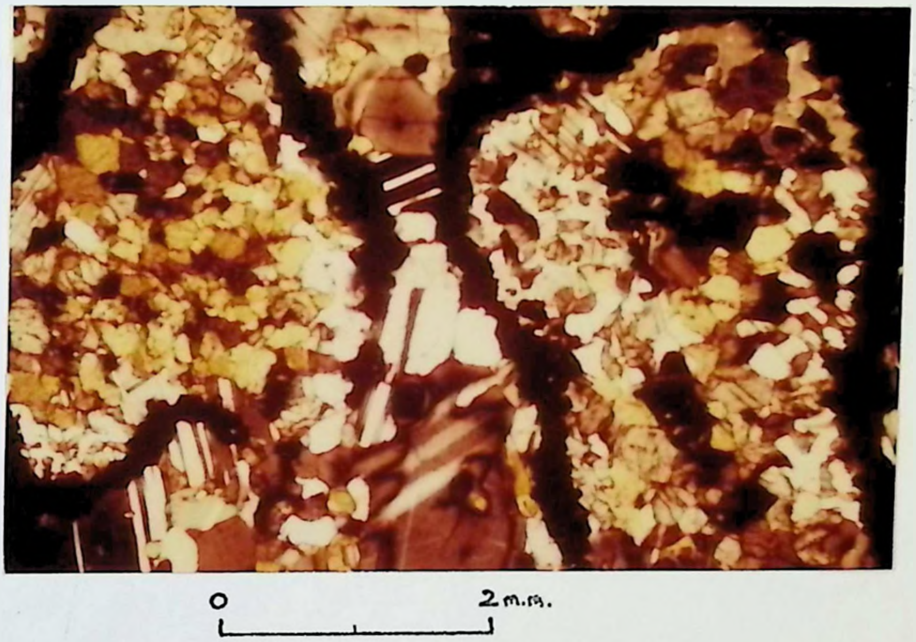


Plate 5-9 Chain of sub- to eu-hedral garnets (black) rimming orthopyroxenes from Green Feldspar Facies rock.

and the development of hornblende and scapolite, rather than a separate metamorphic event. I believe such conditions are an extension of the end game of magmatism beyond that normally found in more rapidly cooled intrusions - in other words they are autometamorphic. Conditions fostering such an autometamorphism are:-

a) Presence of a pervasive ferreous[1] fluid phase

b) Prevailing temperature not far below late stage magmatic temperatures, probably 600-700° C. (Note Luth & Simmons (1966) show from melting experiments on natural anorthosite that a liquid silicate melt is still present at 800° C at 5Kb water vapour pressure.)

c) Intrusion at relatively great depths implies hotter country rock, so that an exceptionally slow cooling rate in the range 600-700° C was encouraged[2].

d) Also due to depth of intrusion a relatively high total and water vapour pressure was evoked. (The relative depth of intrusion is inferred from the fact that the contact aureole is of granulite facies rather than pyroxene hornfels facies.)

In other words, the relatively high temperature and pressure usually associated with metamorphism have, in the case of the anorthosite, been occasioned by a combination of magmatic heat and environment of intrusion and such "metamorphic" conditions were maintained over a far larger time

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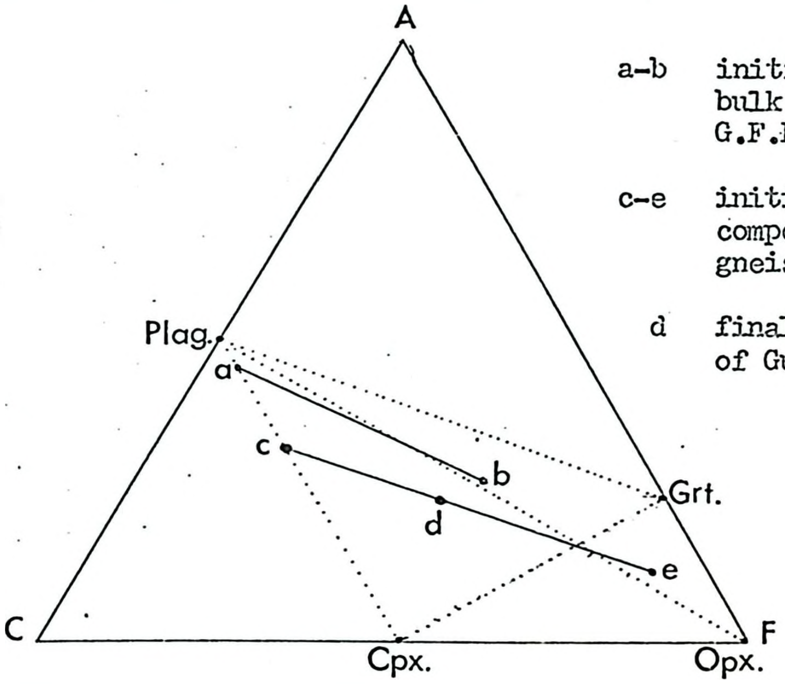
[1] Non-committal on oxidation state.

[2] A very probable contributory factor in this regard is that I believe the anorthosite to have been intruded hard on the heels of the last phase of the "Grenville" orogeny and the prevailing isotherms may have been higher than normal for this depth.

period than would be possible in shallower intrusions[1]. Note that "metamorphic" in this sense does not imply any differential movement.

It is in this regime then that the features of the G.F.F. rocks are to be interpreted. Qualitatively I envisage the fluid phase actively promoting and, simultaneously, acting as a medium for the mosaic recrystallisation of the pyroxenes (and the plagioclase) and, because of the composition of this fluid phase the <u>local</u> bulk composition is, in effect, changed towards more Fe rich compositions into the stability field of orthopyroxene and garnet as shown schematically in fig. 5-6.



a-b initial and final local bulk compositions of G.F.F. rocks

c-e initial and final bulk compositions of country gneisses

d final (local) composition of Guadaloupe rocks

<u>Fig. 5-6</u> <u>ACF diagram for the G.F.F. rocks</u>

This does not, of course, explain the observed texture especially the fact that the garnet and orthopyroxene are not contiguous. In discussing the coronite amphibolite a similar feature was noted in which the growth of clinopyroxene and orthopyroxene are apparently associated with

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[1] Very slow cooling conditions have already been appealed to, to explain exsolution in the pyroxenes and the large, unzoned plagioclase and pyroxenes.

the breakdown of garnet but the two are spatially distinct. It is proposed that during the development of metamorphic rocks (with no concomitant movement) the various reactions take place, not on the straight forward basis of $A+B \rightleftharpoons C+D$, but rather a whole series of inter-related reactions occur along a spherical chemical gradient (see Bartholomé 1960). Such appears to have been the case in both the development of the coronite amphibolite and the G.F.F. rocks; similar localised chemical gradients will be shown to be operative during the development of the garnet and epidote in the marginal foliated facies and in the uralitisation of the pyroxene.

Because of their prevalence in this area it is not unreasonable to assume that such gradients are operative in the general case of metamorphic reactions but, due to accompanying differential movements, they are continually destroyed and cannot afterwards be certainly recognised. If this be the case then it follows that minerals involved in a particular pro- or retro-grade reaction need not be in contact -- an important point in defining metamorphic parageneses. Hopefully microprobe analyses will allow a more quantitative evaluation of such gradients in the case of the Whitestone rocks.

On Map I and fig. 5-5 the G.F.F. is shown to be restricted to the core of the body. It is suggested that only in the core did temperatures remain high enough, for long enough to allow development of this granulite facies mineralogy. Nearer the margins the prevailing regime was more akin to the amphibolite facies. Puzzling are the specific controls on the formation of the veins and films in the feldspar responsible for the macroscopic colour: it is not clear whether they are related to the orthopyroxene/garnet reaction or whether they are independently controlled by the composition of the fluid phase and the intensive parameters. The identification of the actual phase present will aid solution of this problem.

In any event it is not inappropriate to remark on the significan of the above discussion to the so-called charnokite problem. Oya Woye

(1962) concludes that various dioritic and monzonitic rocks in Nigeria have strong affinities with the type charnockites of Madras and that they have resulted from recrystallisation of pre-existing rocks under granulite facies conditions while being soaked with Fe-rich liquids; these liquids, he suggests, are derived from the expulsion of H_2O and Fe from rocks being transformed to Mg-rich eclogites at greater depths. If charnockitic kindred rocks are defined as pyroxene-garnet gneisses with dark-coloured feldspars then the present study indicates an Fe-rich fluid phase is indeed important in the genesis of some charnockites at least. In the Adirondacks, de Waard (1966) defines the pyroxene-garnet syenites of the Tupper Saranac complex as being charnockites - see interpretation of origin of these rocks in chapter 4.

In his study of the Guadaloupe complex (see section on oxide exsolution above) Best (1967) describes textures in the middle gabbros which he finds reminiscent of metamorphic granulites and suggests they are due to ".... autometamorphism .... facilitated by slow cooling in the presence of an intergranular aqueous phase" p.441. Both in his figs. 2-5 and fig. 10 and in the text Best describes relations between clinopyroxene/orthopyroxene similar to that described for the G.F.F.[1] Moreover, on p.444 he notes the common occurrence of yellow-brown films of ferric oxide on the mineral grains. Best supposes that the intimate juxtaposition of clino-/orthopyroxene is due to prolonged heating below the solvus (during autometamorphism) which has facilitated the complete granular exsolution of two phases. To explain the preponderance of the ortho-phase he proposes that the originally crystallised pyroxene was a pigeonite which has recrystallised to ortho- and clino-pyroxene - a new wrinkle to the subsolidus pyroxene relations. This rather elegant alternative explanation is rejected for the G.F.F. rocks on the following grounds:-

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[1] Actually the Guadaloupe rocks are more mafic than the G.F.F. and figs. 3 and 4 (Best) are more akin to the polygonal-textured metasomatised gneisses of the contact aureole; in these rocks, because of the abundance of the pyroxenes, the observed relations are confusing.

a) It explains neither the garnet nor the green feldspars which, on the basis of strong circumstantial evidence, are taken to be related to the opx./cpx.

b) Within the G.F.F. the ratio opx./cpx. varies randomly from ∞ to 0.03.

c) There is no reason to suppose the clinopyroxenes of the G.F.F. differ from those of the more normal anorthosite and none of these have a composition indicating the possibility of any exsolution.

On the other hand Best, as well as noting the similarities of the textures to metamorphic rocks, notes that the Guadaloupe pyroxene pairs are akin to granulite facies pyroxenes in both overall composition (his fig. 8) and in the partition of Fe and Mg between the two phases (his fig. 9) as defined by Binns (1962), Bartholomé (1962) and Kretz (1963). If, then, my hypothesis is applicable to the Guadaloupe rocks the data in Best's Tables 2 and 3 indicate that a volume for volume replacement of clino- by ortho-pyroxene involves the following cationic adjustments expressed in cation % relative to clinopyroxene:-

a) Increase of 50% Fe^{3+}, 50% Fe^{2+} and 20% Mg. (First two mainly from fluid phase)

b) Decrease of 90% Ca. (Into adjacent feldspar)

c) Si, Al, Ti and alkaliis remain essentially constant.

A possible reason for the lack of garnet in the Guadaloupe rocks is suggested in fig. 5-6.

5c(iv) Uralitisation of the Pyroxenes

A further feature which may slightly modify the local composition of both the primary plagioclase and pyroxene is the development of secondary hornblende. Hornblende is common to virtually all anorthosites but little or no attention has been paid to it; the general consensus would appear to be that it is a mineral developed during the metamorphism of the anorthosite subsequent to its emplacement (implying much later) and, therefore, not of igneous petrogenetic significance. However, a theme of this thesis is that there has been no important metamorphism post-dating the intrusion and the hornblende therefore cannot be so dismissed.

Fig. 5-7 conveniently illustrates the distribution of the hornblende and it is seen that in the strongly foliated marginal areas all the pyroxenes are strongly uralitised while in the core there is little to no uralitisation; in the intermediate area there is wide, rapid and apparently random diversity in the severity of uralitisation making it impossible to realistically subdivide this area (note extreme values of contours for this area). The overall similarity to the degree of scapolitisation is noted (cf. fig. 5-4).

Table 5-7 gives the composition of two hornblendes from porphyritic facies rocks, 278 from the garnet facies and 140 from the epidote facies[1]. Significant is the difference in $\Sigma Fe \times 100/\Sigma Fe + Mg$ of the two hornblendes suggesting that when pyroxenes from the epidote facies are analysed they will prove to be more Mg-rich than those given in Table 5-6.

Table 5-8 summarises chemical data appropriate to a discussion of

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[1] Note, however, rock 140 does not itself contain epidote - but does have trace amounts of garnet.

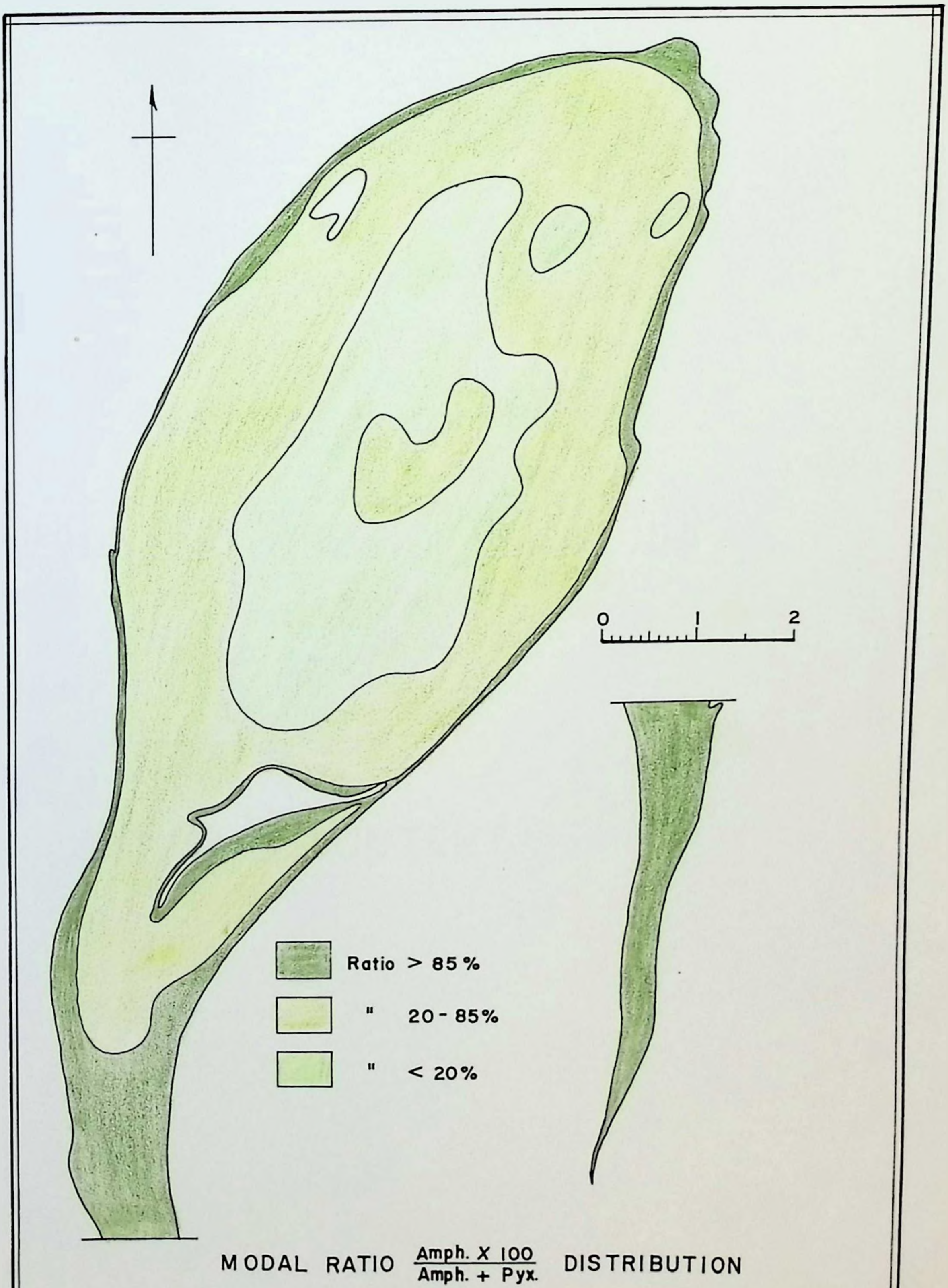
0
1
2
Ratio > 85 %
" 20 - 85 %
" < 20 %
MODAL RATIO Amph. X 100 / Amph. + Pyx. DISTRIBUTION

Fig. 5-7

TABLE 5-7

Analyses of Hornblendes

Lab No	140	278
SiO_2	43.94	41.35
TiO_2	0.82	1.53
Al_2O_3	13.16	13.49
Fe_2O_3	3.30	5.18
FeO	11.29	12.67
MnO	0.22	0.17
MgO	11.68	8.98
CaO	11.51	12.31
Na_2O	1.48	1.08
K_2O	0.85	1.78
H_2O^+	1.76	1.43
CO_2	0.05	0.00
Cr_2O_3	0.02	0.03
Total	100.08	100.00

140 - Green hornblende from porphyritic-facies gabbroic anorthosite. In this rock the pyroxene has been almost completely altered to amphibole and only small cores of pyroxene remain.

$$\frac{\Sigma Fe \times 100}{\Sigma Fe + Mg} \text{ of hble} = 41.0\%$$

This rock is from western part of anorthosite.

278 - Green hornblende from partly uralitised porphyritic-facies gabbroic anorthosite from eastern part of the anorthosite.

$$\frac{\Sigma Fe \times 100}{Fe + Mg} \text{ hble} = 52.2\%$$

$$\frac{\Sigma Fe \times 100}{\Sigma Fe + Mg} \text{ pyx} = 50.8\%$$

Structural formula on basis of (a) 24 & (b) 23 oxygens:

	(a)	(b)		(a)	(b)	
Ca	1.81	1.80		1.99	1.97	
Na	0.42	0.42	X	0.32	0.31	X
K	0.16	0.16		0.34	0.34	
Mg	2.56	2.54		2.02	2.00	
Fe^{+2}	1.39	1.38		1.60	1.58	
Mn	0.02	0.03	Y	0.02	0.02	Y
Fe^{+3}	0.37	0.37		0.59	0.57	
Ti	0.09	0.09		0.19	0.17	
Al	0.74	0.77		0.64	0.55	
Al	1.54	1.58	Z	1.76	1.82	Z
Si	6.46	6.42		6.24	6.18	
OH	1.73	2.00		1.44	2.00	

the uralitisation. Petrographic examination shows:-

1) Usually (probably invariably) the plagioclase abutting on the amphibole rim is more Ca-rich than the rest of the same grain.
2) Abundant blebs of quartz occur in the amphibole in the vicinity of the pyroxene/amphibole interface (Plates 5-10 and 11).
3) Adjacent to the amphibole rim there is no oxide-exsolution in the pyroxene and any irregular re-entrants of amphibole into the pyroxene (controlled by cleavage etc.) are matched by equivalent re-entrants in the oxide-free area of the pyroxene.

From these observations and the data in Table 5-8 it is deduced that the amphibole has developed not simply by hydration of the pyroxene but through a complex reaction involving pyroxene, adjacent plagioclase and the fluid phase. Qualitatively it appears that excess Ca ions of the pyroxene not required by the amphibole migrate to the adjacent plagioclase in exchange for Na. Simultaneously some of excess Fe and Ti required by the amphibole has been 'leached' from the pyroxene, possibly <u>before</u> exsolution of the oxides from the pyroxene, but possibly some Fe and Ti was also supplied by the fluid phase. The excess Si is present as quartz blebs. To account for the change in Mg and Al it is proposed that some plagioclase has been incorporated into the amphibole thus supplying excess Al as well as diluting the Mg from the pre-existing pyroxene. Fig. 5-8 diagrammatically portrays the envisaged exchange reactions.

The presence of similar cationic gradients in the coronite amphib-

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[1] These areas may well be equivalent to the bleached areas in pyroxenes often noted adjacent to uralitic hornblende (see Deer, Howie & Zussman, Vol.II, p.131).

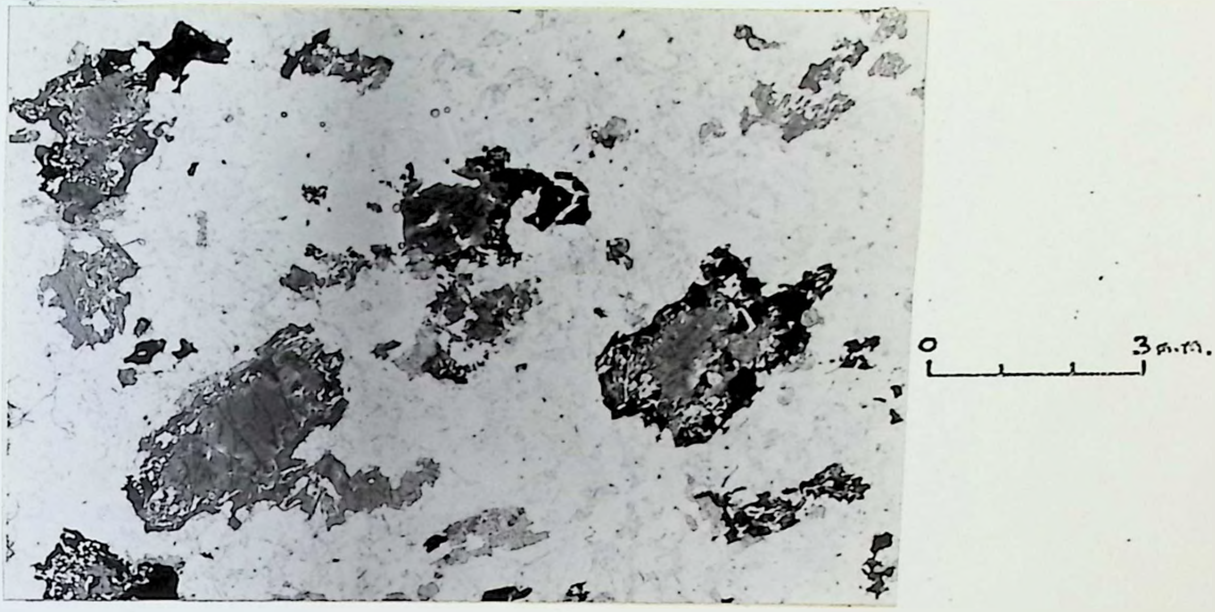

Plate 5-10 Amphibole (dark grey) rimming clinopyroxene (light grey) in porphyritic facies anorthosite. Plane.
Note abundant quartz blebs in amphibole. Very light grey mineral in plagioclase is interstitial scapolite.

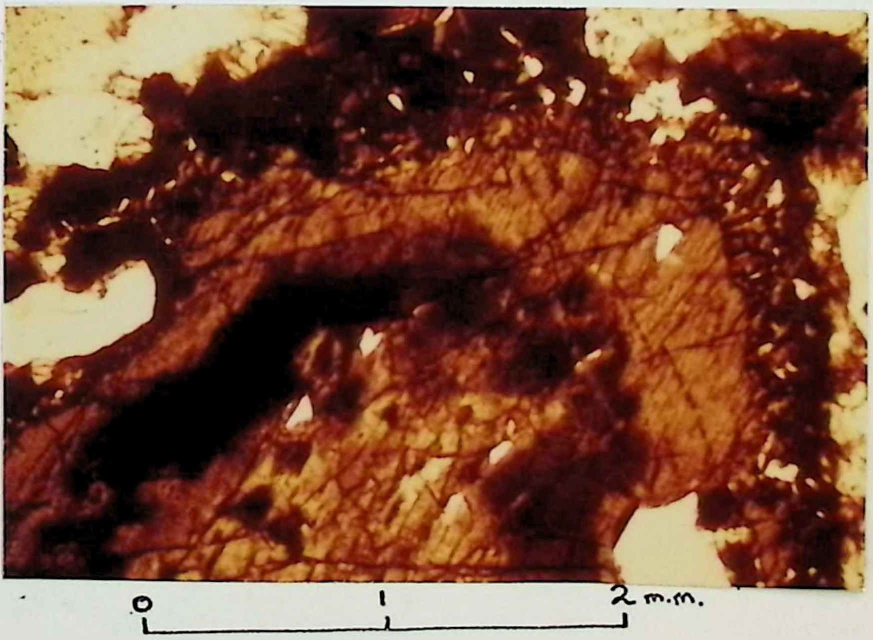

Plate 5-11 Quartz blebs in amphibole (black) rimming clinopyroxene (dark brown) - plane.
Dark area in central area of pyroxene is unusually rich in oxide dust and, while not well illustrated, the core of the pyroxene has orientated oxides. Note that edge of pyroxene is free of both type of oxides.

TABLE 5-8

Chemical Comparison of Pyroxene 278 and its Secondary Amphibole

(a) Cations on basis of 24 oxygens

	Ca	Mg	Fe^{+2}	Mn	Fe^{+3}	Ti	Na	Al	Si
Pyroxene	3.42	2.36	1.08	0.04	0.32	0.08	0.24	1.04	7.32
Amphibole	1.99	2.02	1.60	0.02	0.59	0.19	0.66	2.40	6.24

(b) Assuming that equal nos. of oxygens imply approximately equal volumes then cation exchanges involved in transferring a unit volume of pyroxene to one of amphibole are:-

	Cations to be added	Surplus cations	Cation change in % relative to pyroxene
Ca	-	1.43	-42%
Mg	-	0.34	-14%
Fe^{+2}	0.52	-	48%
Mn	-	0.02	
Fe^{+3}	0.27	-	84%
Ti	0.11	-	138%
Na	0.42	-	175%
Al	1.36	-	131%
Si	-	1.08	-15%
OH	2	-	
Total	3.68	2.87	

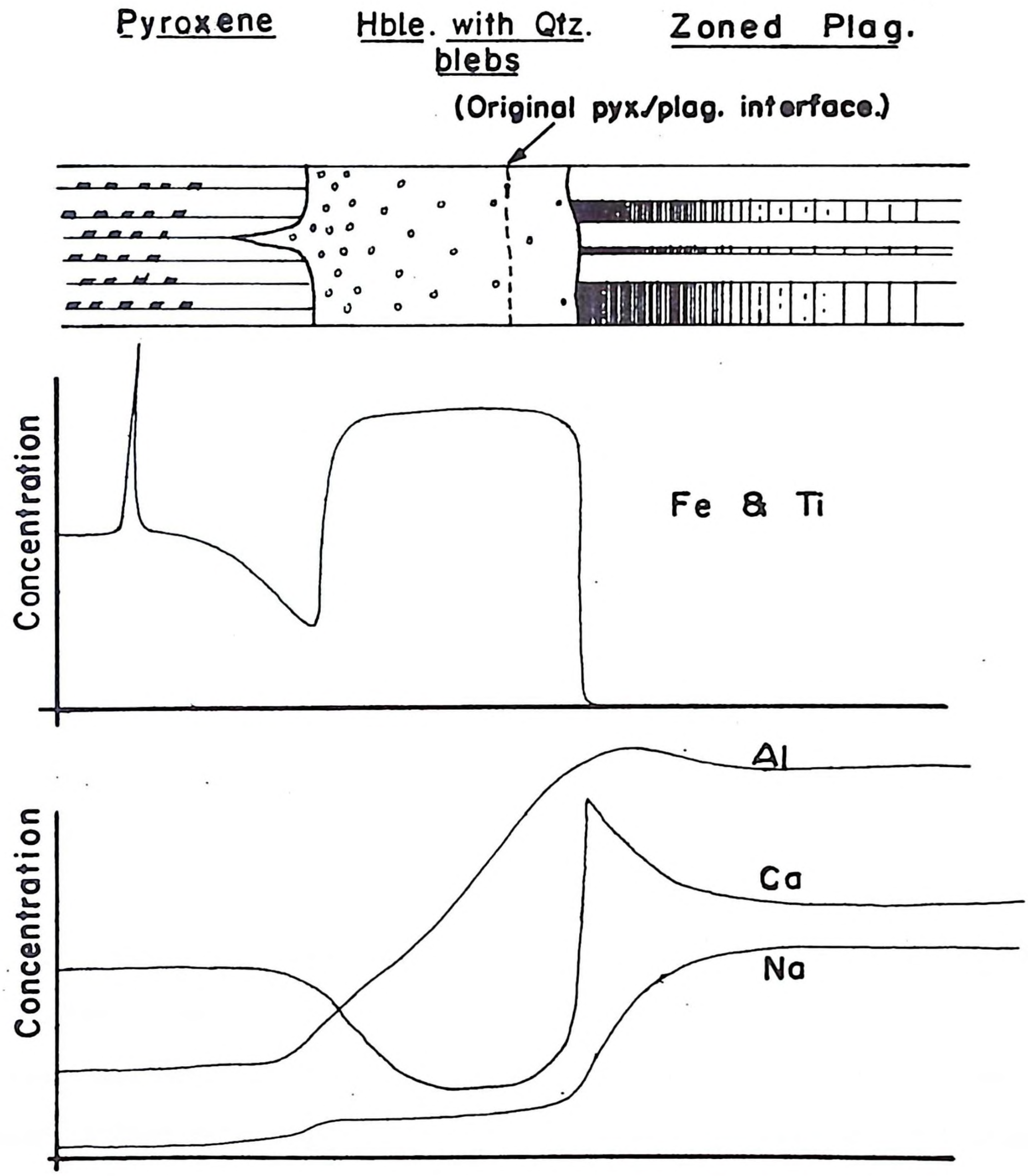

FIG. 5-8 Diagrammatic representation of the uralitisation.

olite, scapolitisation and development of orthopyroxene is recalled and the varied nature of such gradients plus the unknown contribution of the fluid phase renders an attempt to compose balanced reactions to cover such situations merely an academic exercise in chemical accountancy.

Examination of the topology of the amphibole/pyroxene relations reveals that the uralitisation preceded slightly the recrystallisation of the pyroxenes - see Plate 5-3. In a later section it will be shown that the recrystallisation occurred during the autometamorphic episode therefore the uralitisation cannot be due to a (much) later metamorphism: in fact the development of hornblende is taken as yet another indication of the presence of a fluid phase active during a protracted magmatic end game.

5d. Oxides-Garnet-Epidote

Figs. 5-9,10 and 11 support the observations of chapter 2 that garnet and epidote are, in general, restricted to the foliated facies with strong presumptive evidence that which of the two index minerals is developed is a function of the oxide distribution. Independent evidence from the contact aureole and the anorthosite indicates there has been no significant metamorphism subsequent to the intrusion of the anorthosite. Rather limited data compiled in fig. 3-2 illustrates that the foliation in the anorthosite, while conforming with the general strike of the regional foliation along the length (N/S) of the anorthosite, differs in dip from the regional dip and does so differently in the three sub areas W, N and E (see fig. 3-2). This is consistent with the foliation in the anorthosite resulting from stresses consequent on the intrusion of the anorthosite and is less readily harmonised with a hypothesis correlating the

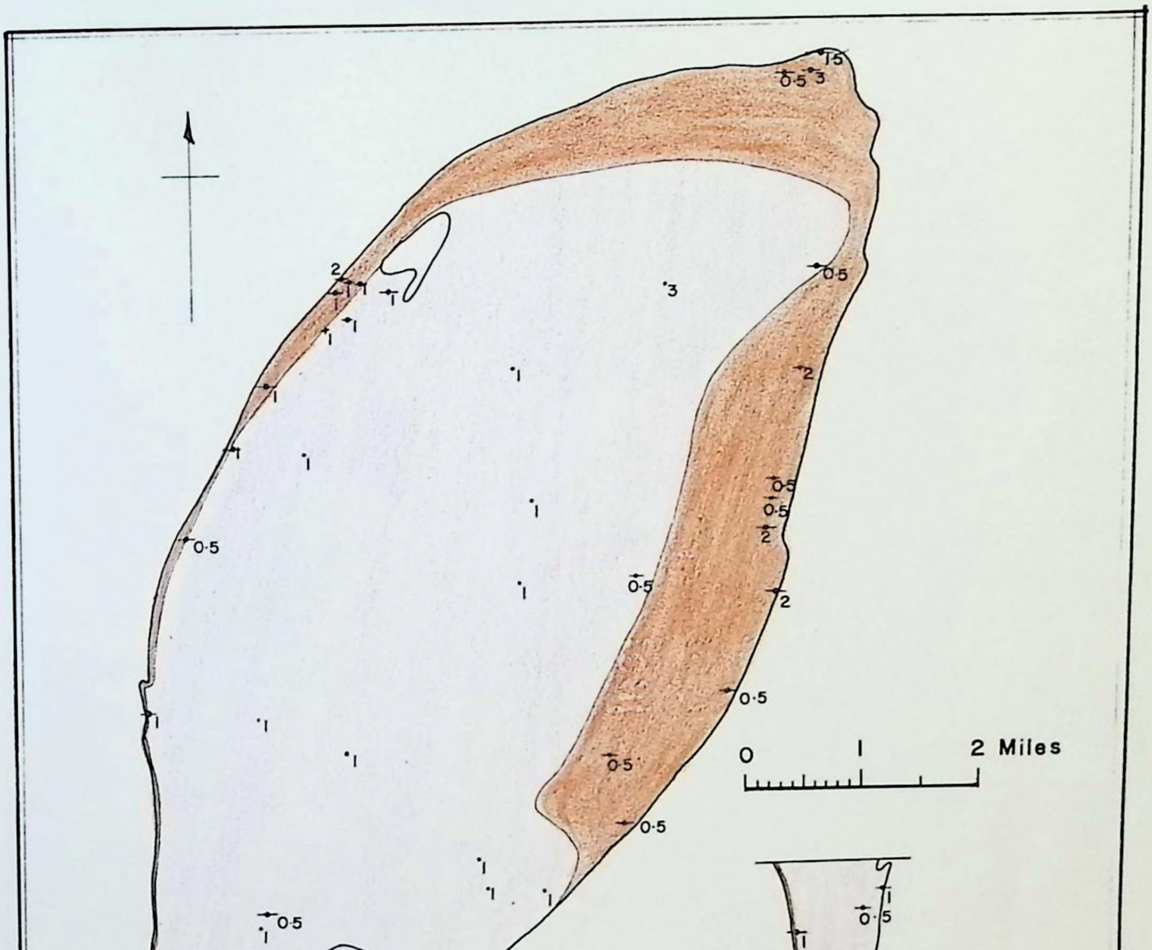
1.5
0.5
3
2
1
1
1
1
1
0.5
3
1
2
1
1
0.5
0.5
2
1
0.5
0.5
2
1
0.5
1
1
0.5
1
0.5
1
1
1
0.5
1
1
0.5
3.5
1.5
1
0.5
1
1
0.5
1
1
1
1
1
1
2
0
1
2 Miles
> 1%
< 1%
'Rogue' Opaques (%)
Sphene > Trace (%)
MODAL OPAQUE DISTRIBUTION

Fig. 5-9

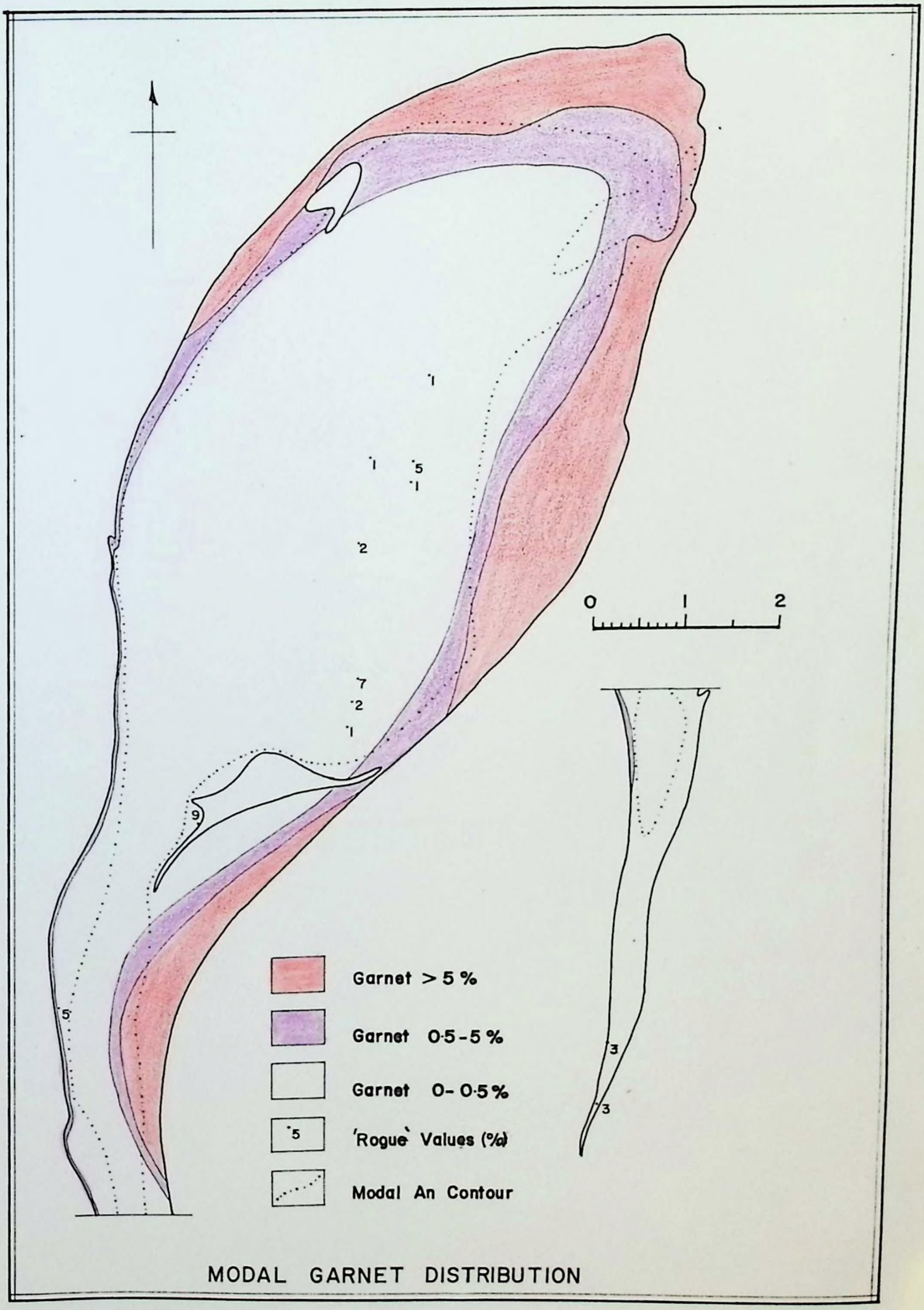
0
1
2
Garnet > 5 %
Garnet 0·5 - 5 %
Garnet 0 - 0·5 %
5
'Rogue' Values (%)
Modal An Contour
1
1
5
1
2
7
2
1
9
5
3
3
MODAL GARNET DISTRIBUTION

Fig. 5-10

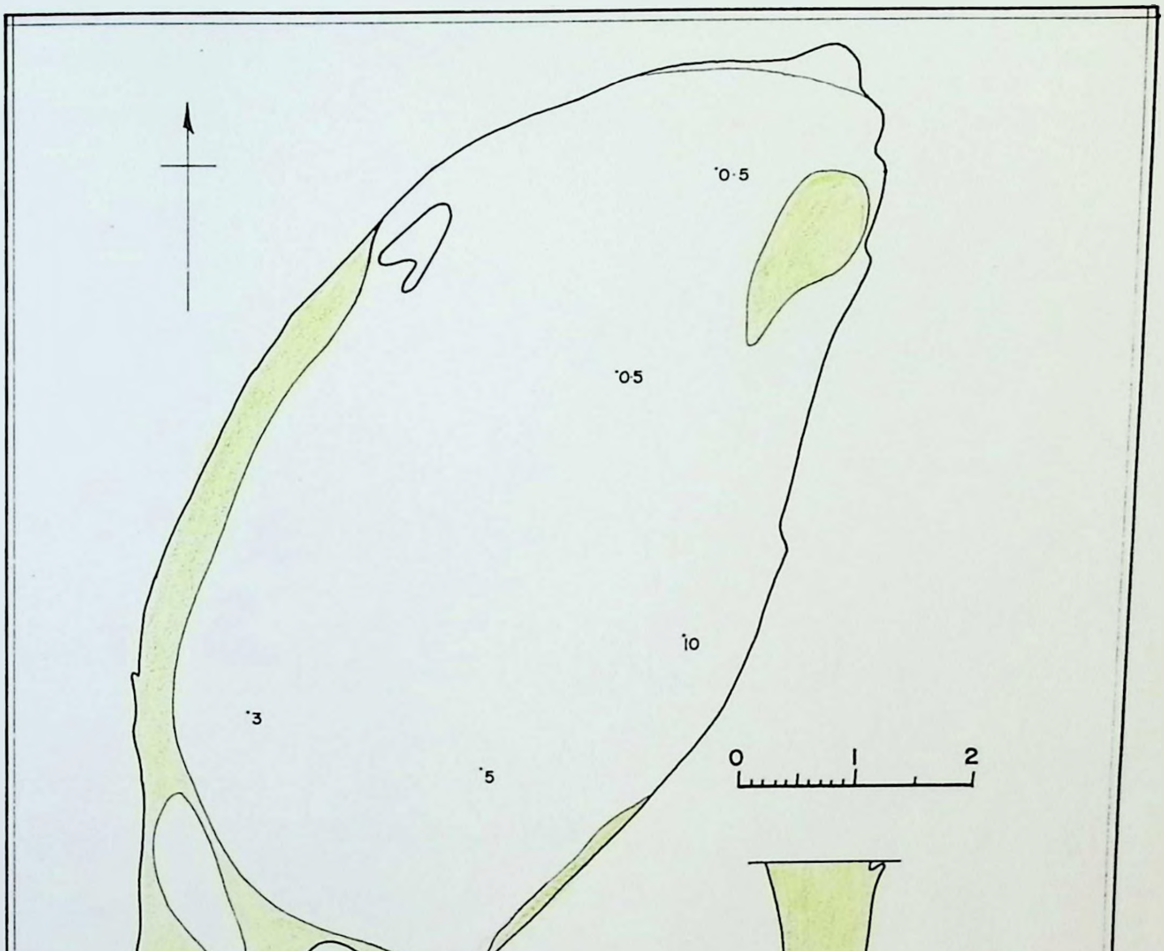

Fig. 5-11

regional and anorthositic foliation. The general restriction of garnet/epidote to the foliated rocks[1] implies a genetic relationship.

5d(i) Oxides

A study of the oxides of the Whitestone anorthosite was conducted by U. Kretschmar (1967) as a M.Sc. thesis and much of the analytical data is based on his work.

The general oxide distribution is shown in fig. 5-9. While indicating that the oxides are concentrated on the east the diagram is misleading regarding the magnitude of this concentration. From Table B-1 (Appendix), on which fig. 5-9 is based, the range in oxides in the slides analysed is trace to 12%. However in the field the wide and local variation of the oxides is obvious (e.g. see Plates 2-15 and 16) and in collecting hand-specimens such local, but abundant, obvious concentrations were avoided so that data in Table B-1 underestimates the oxides[2].

In the irregular oxide concentrations the oxides occur as coarse crystals (up to 1") associated with equally coarse hornblende and garnet (several inches in diameter is common) some 10x to 20x larger than in surrounding anorthosite. The plagioclase in such patches are, however, identical in grain-size, texture and composition to that in the surrounding rock. Even in the "normal" gabbroic anorthosite (i.e. not patently enriched in oxides) the oxides are much the coarsest mineral in the rock and, where the rock is weakly foliated, they are seen to occur with an intercumulus texture. Plate 5-12. Such observations, especially the

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[1] Most rogue values (cf. fig. 5-10 e.g.) are due to development of garnet in the Green Feldspar facies.

[2] Hand-specimens of several pounds containing up to 30% oxides were collected by Kretschmar (1967)

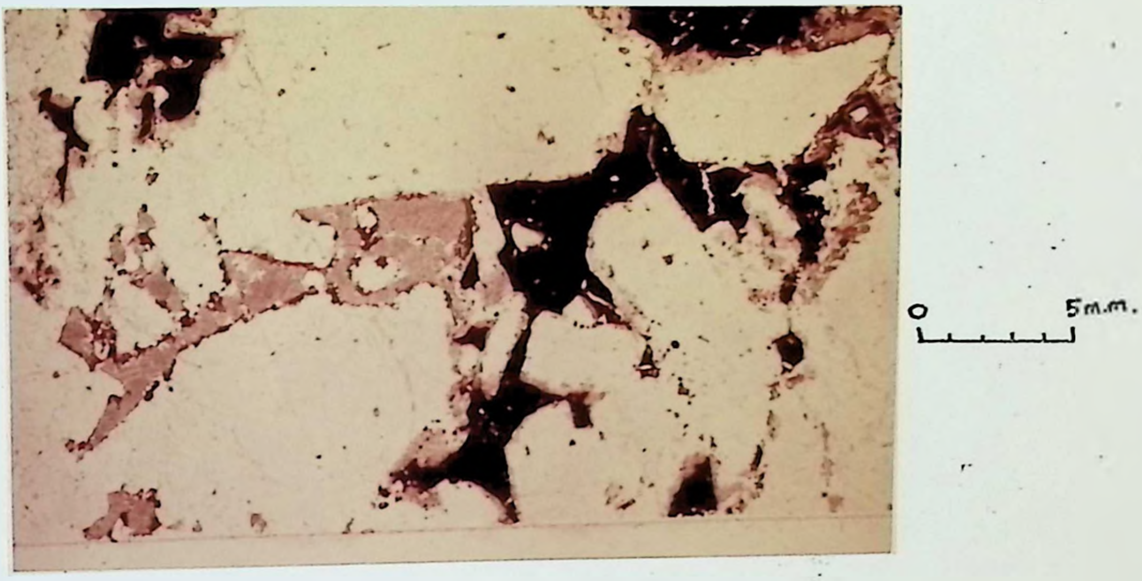

Plate 5-12 Oxides showing intercumulus texture. Compare with adjacent clinopyroxene. Note narrow rim of garnet on oxide and that rock is unfoliated.

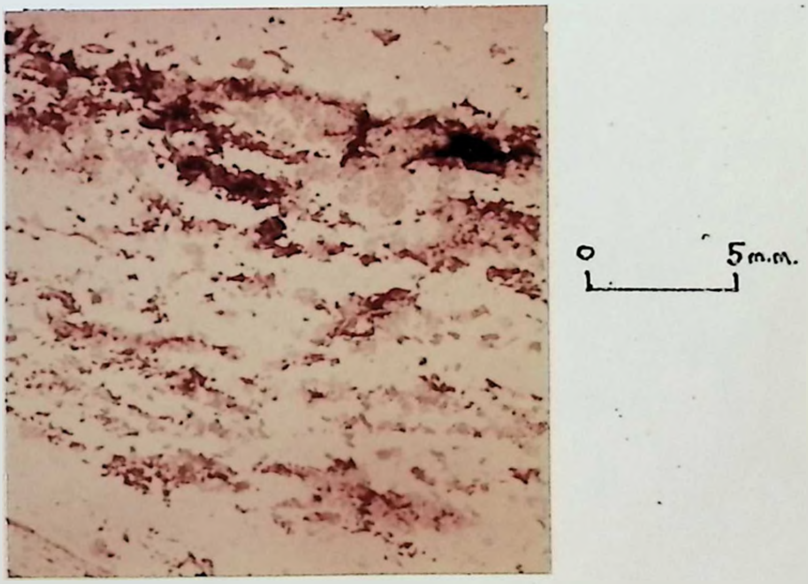

Plate 5-13 In this foliated specimen garnet is now much more abundant and oxide is correspondingly rarer than in 5-12. Note 5-12 and 13 are at the same magnification.

irregular patches, are consistent with the oxides having been precipitated from the *fluid* phase at a late stage in the crystallisation of the anorthosite; such an interpretation will in fact be advanced in the next chapter to account for the unusual differentiation history of the anorthosite and, in particular, the pyroxenes.

In transmitted light the oxides are seen to occur (a) as amorphous rounded blobs surrounded by garnet and/or hornblende clots in strongly foliated rocks or (b) with an intercumulus-type texture surrounded by a very narrow rim of garnet in weakly foliated rocks c.f. Plates 5-12 and 13 and note antipathetic relation of garnet and oxide. Another significant feature is that the oxide is practically never in contact with plagioclase. Most common are coronas of garnet and amphibole; sphene also occurs fairly regularly as narrow rims on the oxide and in a few cases scapolite insulates the oxide from the plagioclase.

In polished section the oxides are seen to consist of clots of magnetite (virtually free of Ti[1]) and irregular grains of hemo-ilmenite with lamellae of ilmeno-hematite exsolved on the basal plane. These lamellae themselves usually contain exsolved lamellae of hemo-ilmenite identical in composition to that of the host hemo-ilmenite[1]. In virtually all cases lamellae in the hemo-ilmenite die out and disappear as they approach the homogeneous (and often euhedral) magnetite. See Plates 3 and 4, Kretschmar. From X-ray data Kretschmar estimates the hemo-ilmenite to have a bulk composition of $Hem_{44}Ilm_{56}$ - the ilmenite lamellae containing a maximum of 10% hematite in solid solution and hematite lamellae a maximum

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[1] Based on electron probe analyses by Kretschmar (1967).

of 30% ilmenite in solid solution[1].

On the face of it such data indicates that the oxides crystallised in the high fo$_2$ region of Buddington and Lindsley's figure 5 (1964) - an area for which no analytical data is available because of interference of the solvus. Unfortunately the data are insufficient to be even reasonably semi-quantitative. A high Po$_2$ is consistent with the lack of sulphides in the body, the sulphur appearing as SO$_3$ in the scapolite.

Since the anorthosite is presumed to have been unaffected by any serious tectonism since its consolidation it is deduced that the present conformation closely approximates that obtaining during the final consolidation. Fig. 5-12 illustrates an interpretive section across the main part of the anorthosite (South of Snakeskin Lake). The anorthosite is thought to plunge gently to the NNE.

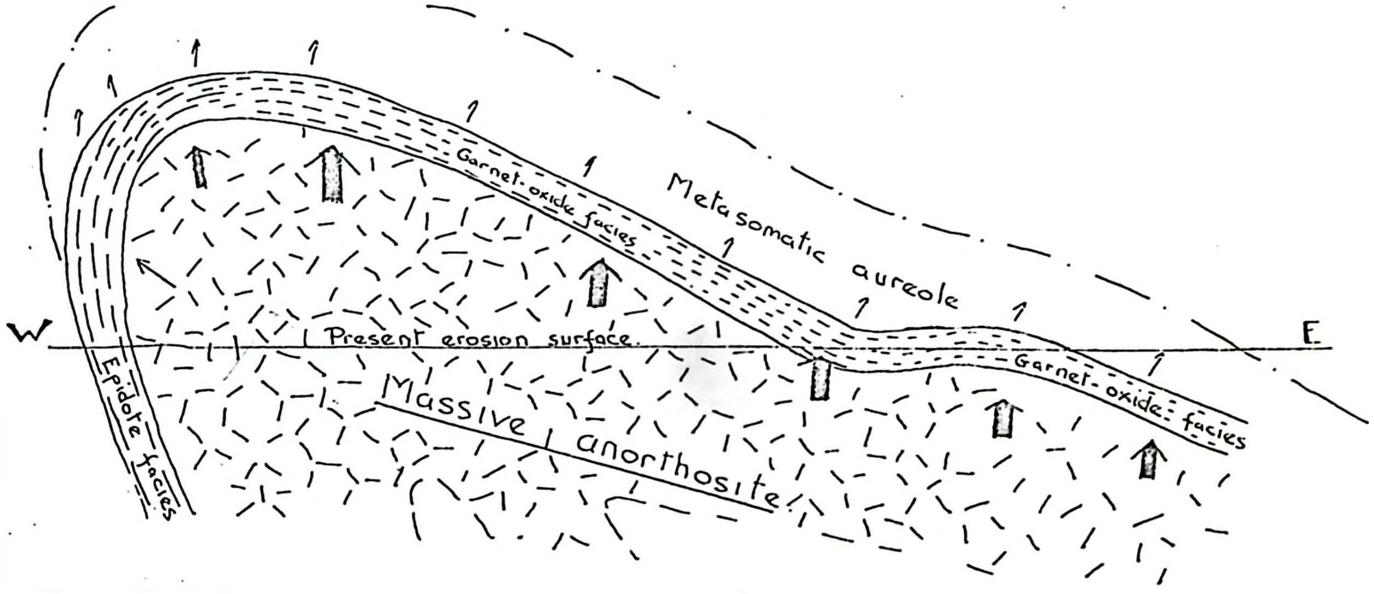

Fig. 5-12 Diagrammatic section across anorthosite illustrating movement of late stage ferrous fluids

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[1] Based on electron probe analyses by Kretschmar (1967).

Proposing that the fluid phase tended to migrate upwards and that this phase was responsible for both the metasomatic aureole and the oxides in the anorthosite, then the distribution of these two phenomena are explained by this diagram.

5d(ii) Garnet-Epidote

Whatever the origin of the oxides evidence for the oxide-garnet-epidote relations, outlined above and in chapter 2, is abundant on all scales from the complete pluton down to individual thin sections.

The analysis of a garnet is given in Table 5-9 with one from the Adirondack anorthosite for comparison. A surprising feature is that despite the strong spatial association of garnet and oxide the garnet is not notably enriched in the almandine molecule -- the relatively high pyrope and grossularite are remarkable.

The antipathetic modal relationship of garnet and oxide demonstrated by the extreme cases shown in Plates 5-12 and 13 is recalled, and that the abundance of garnet corresponds to the severity of the foliation. This supports the contention that the conditions governing the development of the foliation encouraged the growth of the garnet. On the other hand, it may be misleading to overstress the association of garnet and oxide: the garnet often occurs with no obvious relation to the oxide and frequently occurs more intimately related to the pyroxene/amphibole minerals, occurring outboard of the amphibole.

The garnet commonly contains rounded blebs of sphene (note garnet is very low in TiO_2). Other common inclusions are rounded blebs of plagioclase. Commonly textural relations are found indicating that the garnet is replacing the plagioclase. Most illuminating are cases of almost euhedral but incomplete garnet crystals "eating their way" into

TABLE 5-9

Garnet Analysis

	A	B
SiO_2	38.70	37.48
TiO_2	0.11	0.66
Al_2O_3	20.93	21.01
Fe_2O_3	1.16	1.12
FeO	24.40	27.25
MnO	0.64	0.82
MgO	5.19	3.48
CaO	8.83	8.45
Na_2O	0.04	0.07
K_2O	0.03	0.03
P_2O_5	0.00	n.d.
H_2O	0.05	0.11
	100.08	100.48

A Garnet from foliated gabbroic anorthosite No. 90. Analyst J. Muysson, McMaster.

$Alm_{53.5}$ $Py_{20.4}$ $Gross_{21.0}$ $And_{3.8}$ $Spess_{1.3}$

B Garnet from gabbroic anorthosite gneiss, road cut east of Long Pond outlet, Willsboro Qd. Adirondacks.
Analyst L.C. Peck. (Buddington 1950)

$Alm_{60.3}$ $Py_{13.9}$ $Gross_{20.7}$ $And_{3.3}$ $Spess_{1.8}$

Structural formulae on basis of 24 oxygens

Ca Mn Fe $^{2+}$ Mg	1.47 0.08 3.17 1.21	5.93
Al Fe $^{3+}$ Ti	3.84 0.14 0.01	3.99
Si	6.03	

plagioclase, the immediately adjacent plagioclase being lower in Ca than normal - see grossularite content in Table 5-9.

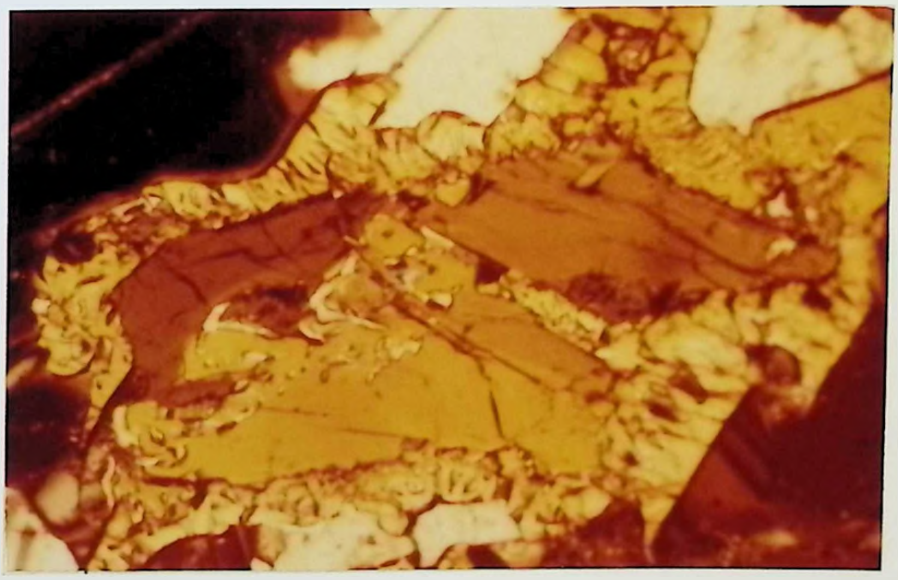
Such relations, taken with the chemical analysis, indicate that the growth of the garnet involved participation of oxides, pyroxene/amphiboles and plagioclase inferentially similar to that of uralitisation, scapolitisation etc. but in this case spatial relationships have been modified by the simultaneous development of the foliation. The involvement of pyroxene in the garnet forming reaction would seem to be required by the garnet's pyrope content.

The corona nature of the epidote and its relation with the mafic (non-opaque) minerals is particularly well displayed in thin section (Plate 5-14). The epidote is colourless but with a middle 2nd order maximum birefringence - sections with lower birefringence show anomalous blues. The d-spacing calculated from the 020 reflection indicates a composition around half way between clinozoisite and epidote, containing 8±1 wt % Fe_2O_3, using graph in Myer (1966). The chemical analysis of a clinozoisite from a West Greenland anorthosite given by Ellitsgaard-Rasmussen & Mouritzen (1954) shows 5.48% Fe_2O_3.

The epidote corona on the mafic minerals is almost invariably a myrmekitic intergrowth of plagioclase and epidote as illustrated in Plate 5-14. Close examination reveals that the plagioclase is continuous with the adjacent plagioclase grains and there is a compositional difference between such plagioclases. That is, the (hydrous) epidote has developed exactly analagously to the garnet by a reaction involving the pyroxene-amphibole, plagioclase and the fluid phase.

The development of garnet and epidote slightly post-dated

<u>Plate 5-14</u> Corona of myrmekitic epidote on amphibole - plane. In this case the primary pyroxene has been completely uralitised to an amphibole/quartz symplectite. Note regularity with which epidote rims this secondary uralite.



<u>Plate 5-15</u> Same specimen at higher magnification - nic. Note halo in plagioclase at left abutting on the epidote.

0 1 2 m.m.

the uralitisation (Plate 5-14) and was probably the final stage in the development of the border foliated facies.

5e. Other Minerals

Olivine?

Apart from the Michikamau intrusion which differs in several other aspects, olivine would appear to be absent in the majority of massif type anorthosites. However, at several localities in the core of the Whitestone body (identified on fig. 5-5) thin sections show the presence of irregular patches of serpentine and a carbonate (dolomite?) from which patches there radiates cracks in the feldspar (Plate 5-16). Although the ratio of serpentine/carbonate is not constant nor do the patches reveal any pseudomorphic form they are interpreted as altered olivines. Although they do not occur in any great amounts, if they are indeed olivine, they are of petrogenetic significance.

Carbonate

Apart from patches noted above, carbonate also occurs in trace amounts as irregular pools in several thin sections mainly from the garnet facies. They may very well have been precipitated from the fluid phase - however, country rock contamination is also open.

Apatite

Somewhat rounded grains occur in the rocks of the garnet facies - often intergrown with the oxides and it seems certain they are a product of the fluid phase. Apatite never occurs in greater than trace amounts.

Quartz

Apart from quartz blebs in the uralitic amphibole, quartz also

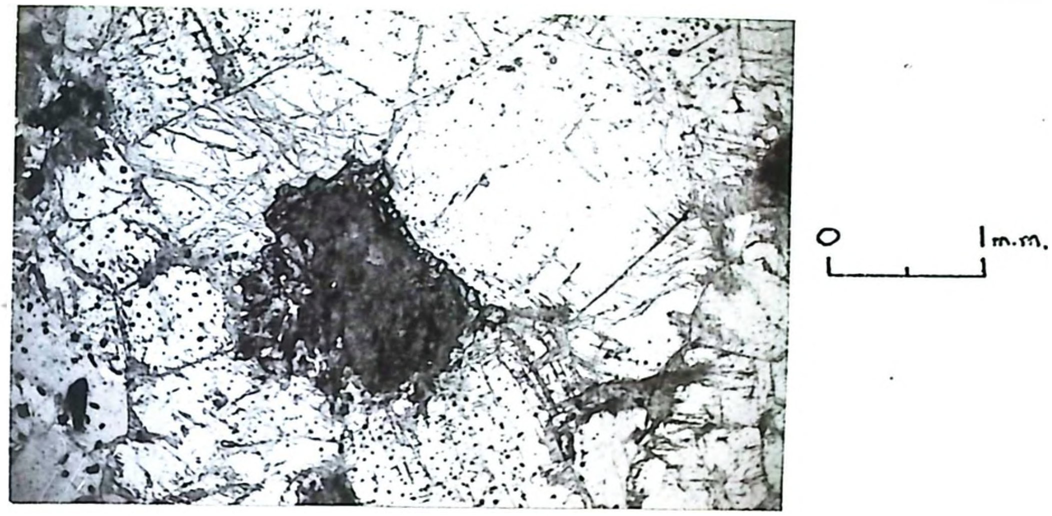


Plate 5-16 Serpentine/calcite patch in anorthosite - plane.
Note radiating cracks in feldspar surrounding the serpentine.

occurs in very minor amounts in the matrix of the anorthosite mainly in the marginal areas of the eastern area. It occurs in small (0.05-0.2 mm) blebs. It is not clear whether, in such rocks, quartz is due to marginal contamination or is a product of some of the complex reactions prevalent in this area. There is nothing to indicate it is of primary origin.

Micas

Biotite occurs sporadically in severely uralitised rocks mainly as a cleavage alteration of the hornblendes. It is usually restricted to rocks near the contacts with the country rock, but with this restriction can occur anywhere along the margin of the body. Muscovite and chlorite, however, which have a similar habit to the biotite, are confined to marginal rocks in the narrow tail of the anorthosite.

5f. Fabric of the Anorthosite

A generally accepted property of massif anorthosites is the cataclastic texture of the plagioclase which is usually taken to indicate irruption of the magma in a highly crystalline state (Buddington 1939, Lacy 1960, Berrangé 1965). Higgs (1954), on the other hand, attributes much of the cataclasis to explosion shattering due to volatile build-up at a late stage in the magmatic history. Berrangé (1965) considers this feature coupled with a very coarse, primary grain-size as a characteristic feature of orogenic-plutonic anorthosites diagnostic in distinguishing them from gravity-stratified bodies whose dominant textural features are lack of large crystals and presence of cumulate textures - apparently implying cumulate textures are absent in massif-anorthosites, a conclusion with which Romey (1968) would disagree. Further, such authors as Kranck

(1963), Hargraves (1962), Philpotts (1966) (inter alia) have noted the ubiquity of recrystallisation as a petrographic feature but they are not specific on its origin, apparently implying it is due to a later metamorphism and not, therefore, of petrogenetic significance. This section will discuss these various aspects of the fabric of the Whitestone anorthosite.

5f(i) Recrystallisation

In the Whitestone body recrystallisation is evident to some degree in every slide examined and in the last sections the diagnostic features of the primary and recrystallised grains were noted. Plates 5-17 and 18 illustrate the relation of the primary and recrystallised grains for both pyroxene and plagioclase and their essential similarity is noted. On this basis then, the following discussion is focused on the plagioclases since, because of their abundance, relatively large domains of most thin sections can be considered as a single phase aggregate. .

Notes on Recrystallisation and Strain[1]

Among recent papers on petrography Kretz (1966) and Carstens (1966) have sought to apply the techniques and wisdom of metallurgy to rock textures[2] and these particular works have catalysed the qualitative treatment given here.

In considering the heat-treatment of severely cold-worked (i.e. strain-hardened) materials it is customary in metallurgy to distinguish three, successively higher temperature regions - viz. recovery, recrystallisation and grain-growth. The driving potential for the first two is the stored energy developed during the straining - present mainly as accumulated crystal dislocations; for grain growth it is minimising interfacial (surface) tension.

During recovery no changes in texture can be observed, strain being relieved by dislocation climb, annihilation of dislocations of opposite sign etc. As the temperature of heat treatment is raised nucleation of new, strain-free grains is initiated and, with further heating,

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[1] These introductory notes on the jargon and concepts of recrystallisation are based on "The Structure and Properties of Materials", edited by Wulff (1966).

[2] Note geological fabric term "texture" is equivalent to metallurgical term "microstructure".

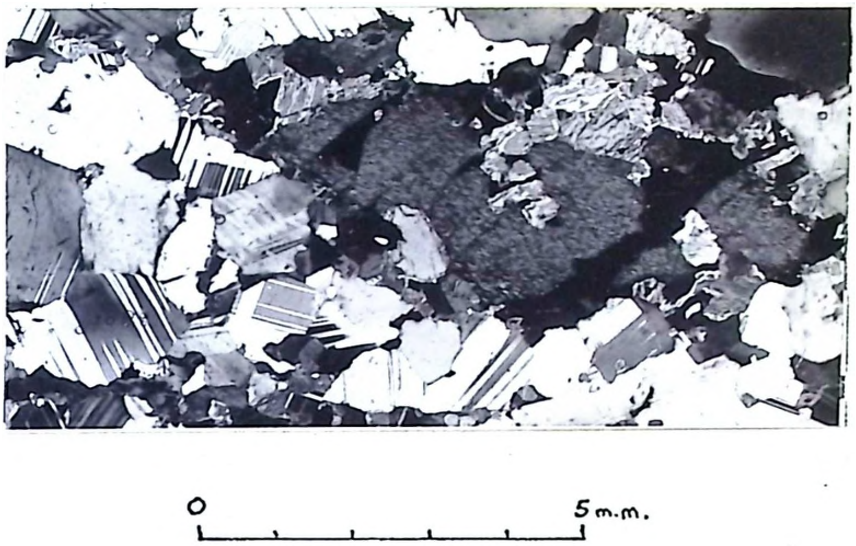

Plate 5-17 Incipient recrystallisation of clinopyroxene - nic. Primary pyroxene with orientated silicate inclusions recrystallising at margins to mosaic of small homogeneous grains.

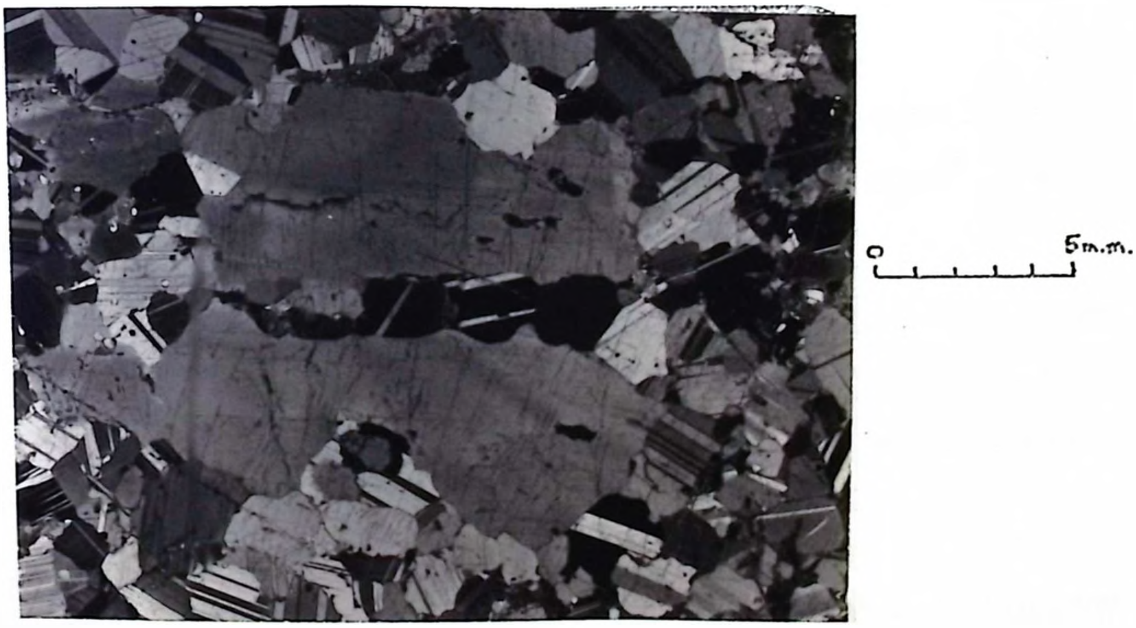

Plate 5-18 Incipient recrystallisation of plagioclase - nic. Large strained grain of plagioclase recrystallising to mosaic of small strain free grains.

eventually the entire sample consists of such strain-free grains. With further heating the grains begin to grow and their final texture is largely determined by interfacial tensions. Since interfacial tensions are essentially independent of grain orientation (see e.g. discussion in Kretz, 1966) then, in the monomineralic case, a balancing of equal tensions results in a polygonal mosaic of equigranular grains with grain boundaries at three-grain junctions averaging 120°.

Since -

$$\Delta f^{*} = \frac{16\Pi\gamma^{3}}{3(\Delta F_V)^2}$$

Δf^{*} = activation energy for nucleation

γ = surface energy of grain (very important for very small nucleii

ΔF_V = energy difference between strained and strain-free state

recrystallisation is more likely if the material has been considerably strained.

Apart from physical properties of the material, important variables in the development of strain are a) temperature and b) strain rate. In the case of monoclinic plagioclase, and considering the high confining pressure (about 75,000 p.s.i.) which is outside the realm of normal metallurgical experience, it is not possible to accurately assess the relative effects of these two variables. In general they act in opposing directions, higher temperature lowering the effect of strain under constant conditions, while increasing the strain-rate increases the effect. It is noted, however, that the percentage increase in strain due to an increased strain-rate is greater at higher temperatures.

Strain in the plagioclase is recognised on such features as flexed and kinked twin lamellae, undulose extinction and taper-twinning[1]. Plate 5-19 illustrates these features.

In the Whitestone anorthosite there is a gradational change in the feldspar textures from margin to core and, to illustrate this, the range has been arbitrarily divided into three types, A, B and C[2] whose distribution are shown in fig. 5-13.

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[1] In taper-twinning individual twins begin to thin in a central part of the crystal in a manner topologically reminiscent of "necking", and gradually retire towards the ends of the crystal. The ultimate stage is presumably untwinned plagioclase; in fact, untwinned grains, usually with undulose extinction, are restricted to highly strained rocks.

[2] Although these various textures have been noted and figured in several papers (e.g. Hargraves 1962) as far as I am aware there has been no systematic, areal study of them, nor has any emphasis been placed on their significance.

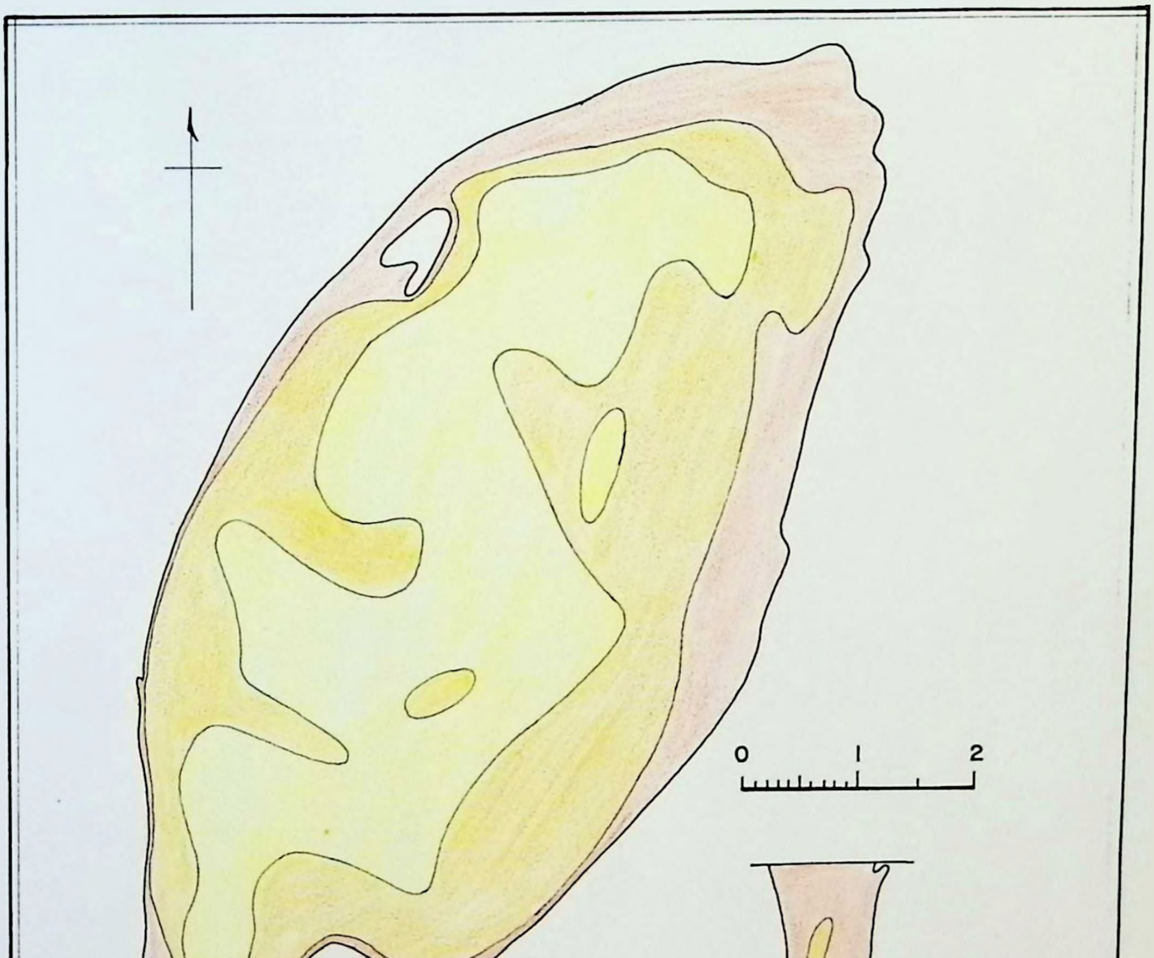

Fig. 5-13

Type A

Confined essentially to macroscopically foliated rocks this plagioclase texture has a typical cataclastic cast as illustrated in Plate 5-19. Grain size is quite variable with occasional, persistent porphyroclasts (highly strained) up to 10 mm. but they average 2 mm.: the granular, attrited grains average 0.1 mm. The ratio of porphyroclast/granular plagioclase has considerable local variation and presumably reflects variation in intergranular movement[1].

Type C

The core of the anorthosite is dominated by an equigranular, equidimensional, polygonal mosaic of unstrained 2 mm. plagioclase grains. In this mosaic 3 grain boundaries averaging 120° are common. Plate 5-20 illustrates a typical thin section.

Type B

This category, transitional between A and C, has some of the properties of each and which dominates is determined by relative position. The texture differs from A in lacking a well-developed cataclastic texture, and from C in lacking straight (or slightly curved) grain boundaries and mensural homogeneity. The feldspars in type B, while the majority are unstrained, have irregular boundaries which tend to be sutured. It is in this facies that the large, dark-coloured, inclusion-filled, primary feldspars are most abundant. Evidence of marginal recrystallisation of these grains are legion. Further, it is only these primary grains that show evidence of strain, but rarely are the earmarks of strain as well

developed as in type A.

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[1] It is this particular texture that has received the most attention in other works.

Plate 5-21 [illegible]

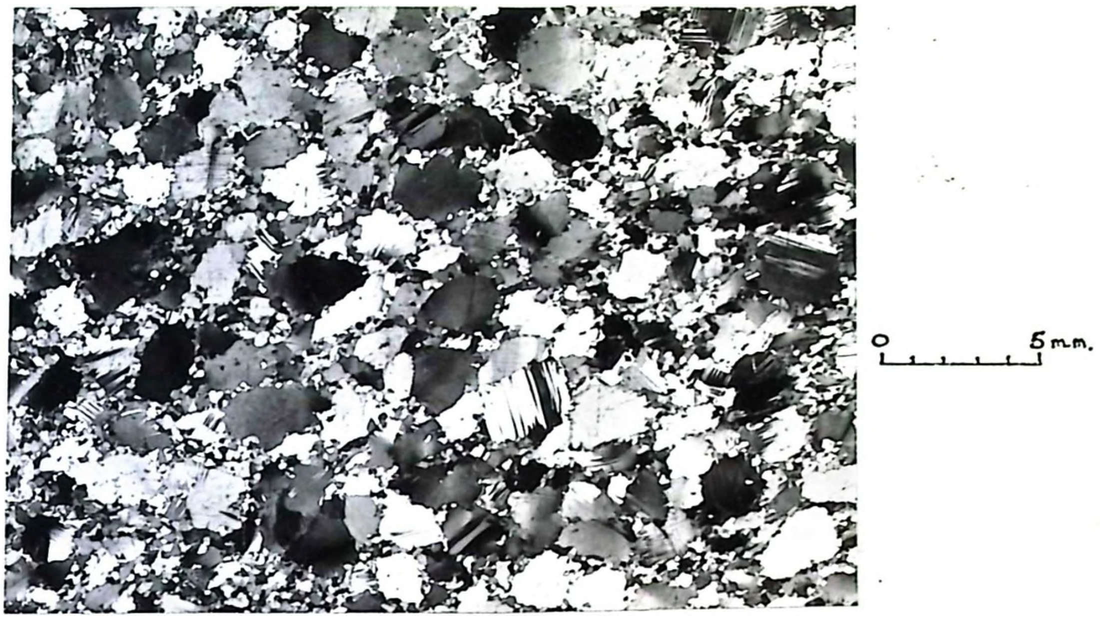

Plate 5-19 Type A plagioclase, unusually well developed.
Note evidence of severe strain in all of the larger grains.

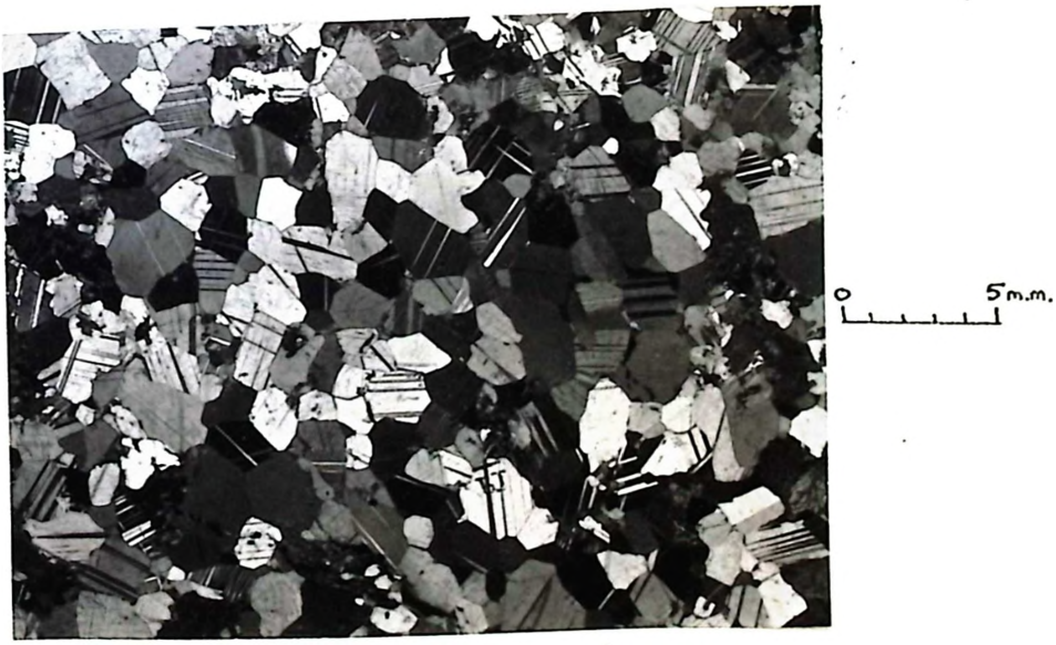

Plate 5-20 Type C plagioclase.
Note lack of evidence of strain, straight-edged, polygonal grains and abundance of 120 three-grain boundaries.

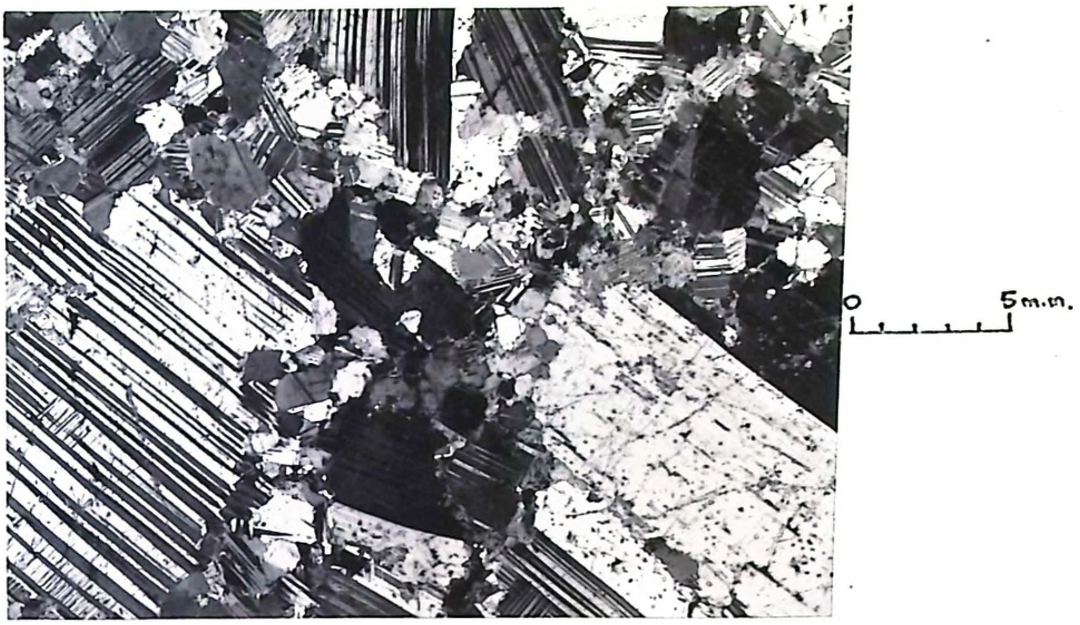

Plate 5-21 Type B plagioclase approaching A-type.
Note large, moderately strained, primary grains which are recrystallising at the margins. In hand specimen large grains are dark blue to purple and recrystallised grains are white.

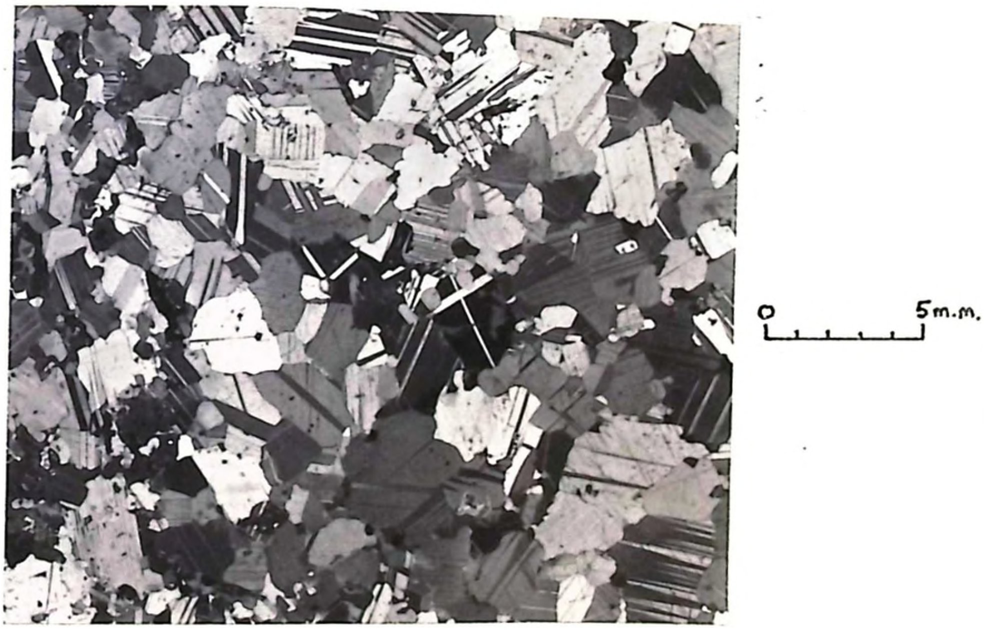

Plate 5-22 Type B plagioclase approaching C-type.
Note absence of large primary grains and absence of evidence of strain. This differs from true C-type plagioclase in lacking straight edges, interfaces being somewhat sutured.

developed as in A. Plates 5-21 and 22 are typical of this facies.

I propose to interpret these textures in terms of strain, followed by annealing recrystallisation during an abnormally protracted cooling history[1]. In explaining the initial strain in the plagioclase the following argument is used:-

1) Evidence from the aureole indicates intrusion post-dates the main, regional orogenesis; this is supported by discrepancy between foliation in country rock and anorthosite noted in fig. 3-2.
2) Since the foliation in the pluton is obvious in the field and is not related to a regional tectonism then the 'movements' responsible for its development could only occur prior to the complete solidification due either to local, paroxysmal, accommodating movements or intrusion of the magma in a crystalline condition.
3) In either case it can be reasonably asserted that the strain would be largely taken up by a marginally developed foliation and such strain is responsible for the cataclastic texture of type A. Despite this concentration of the strain it appears that virtually all the early crystallising plagioclase was strained at least to the extent visible in the primary grains of type B.

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[1] Unfortunately variables involved in estimating heat-loss are, to say the least, imponderable. Even estimating the depth and temperature of the pluton, the crucial question of the disposition and duration of the regional isotherms remain. Note that we are interested in the time interval the rocks remained close to, say, 650°C and not in how long they took to cool through the liquid-solid transformation. I might suggest 500,000 years ± several orders of magnitude.

Whatever the temperature of the magma (i.e. either a fully fledged magma or crystalline mush) it was higher than the country rocks. Although absolute rate of cooling is not known at present it seems safe to assume the margins would cool faster than the core. The distribution of textures shown in fig. 5-13is rationalised on the basis that the foliated rocks did not remain above the annealing temperature, in a static condition, for long enough to allow appreciable recrystallisation. In the area of type B, however, the temperature remained high enough, for long enough, to allow nucleation of small strain-free grains. Only in type C was the initially high temperature prolonged sufficient to allow both recrystallisation and subsequent grain growth during which the balancing of interfacial tensions gave rise to the regular, polygonal mosaic.

In short, I believe the recrystallisation is yet another result of the prolonged post-magmatic cooling interval and is not due to a later metamorphic episode[1]. A very important point arising from this is that, as Plate 5-3 shows, the uralitisation preceded the recrystallisation. It is also noted that while in type A areas the scapolite occurs as ragged interfacial grains or blotches and is almost invariably accompanied by haloes in the adjacent plagioclase (Plate 5-1), in type C areas and to a lesser extent type B, the scapolite tends to occur in regular, polygonal grains lacking haloes - i.e. it has been recrystallised along with the plagioclase. Although relatively common, such evidence is not ubiquitous

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[1] While the tectonic effects of a later metamorphism could conceivably have been concentrated on the margins the problem remains of both straining all the plagioclases and initiating a temperature gradient such as is necessary to explain the distribution of textures. Further, it demands some ingenious Procrustean reasoning to explain this gradient plus the development of garnet and epidote while leaving the contact aureole unscathed.

in type B and C areas so that it seems likely that uralitisation and scapolitisation were essentially coeval, but locally preceded the recrystallisation. The time relations of garnet/epidote and recrystallisation is less certain but it seems reasonable to ascribe them to the movements responsible for the strain; it is noted that both appear to post-date the uralitisation at least (see e.g. Plate 5-14). From these time relations it follows that the volatiles necessary for both the development of hornblende and scapolite were derived from the magma itself.

5f(ii) Textures in other Anorthosites

As noted above, textures individually similar to types A, B and C have been described from various anorthosites but, in most cases, little attempt has been made to explain them. While no data on areal distribution is available it appears that there may be some variation from body to body so that one anorthosite is almost completely type A, etc. On the other hand, two rather different interpretations have been placed on similar textures in the Norwegian anorthosites.

In chapter 1 (p.14) it was noted that Michot J. (1961) emphasises the contrasted nature of the coarse-grained, strained, sutured, inclusion-filled feldspars of the para-anatectic anorthosite and the smaller, unstrained, regular, inclusion-free polygonal feldspars of the anatectic noritic anorthosite. In the case of the Whitestone body I think it would be difficult to reconcile many other features with an anatectic origin for the core of the anorthosite.

Also in an Egersund anorthosite[1] Carstens (1966) has described

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[1] Unfortunately it is not clear from the text from which of the various bodies recognised by Michot in the Egersund area this specimen comes.

porphyroblasts of plagioclase surrounded by an irregular mosaic of 1-2 mm, plagioclases. He ascribes these porphyroblasts to abnormal grain growth; however his fig. 2, which can be compared directly with Plate 5-21, shows that the porphyroblast is highly strained, with curved twin lamellae while the granular mosaic has regular, well-developed twins. I suggest that a recrystallisation history similar to type B is a more appropriate interpretation of this particular rock.

5f(iii) Primary Textures

Directly due to the pervasive recrystallisation practically all features of the primary texture must be inferred. From the evidence of the remnants of the primary plagioclase and the lath-shaped areas in the glomerules (Plate 2-3 and 5-2) it is deduced that the feldspar originally had a grain size of one to several centimetres - the larger sizes occurring in the plagioclase rich domains. Even the largest of the plagioclase grains (>6 cm.) lacked compositional zoning. No evidence could be found indicating the presence or absence of layering of the plagioclase laths such as is found e.g. in the Morin (Philpotts 1966) and Sept Iles anorthosites (Faessler 1942).

The glomeropoikilitic texture (Plate 5-2) is taken to represent an exaggerated poikilitic texture. Even in these large grains (up to 10 cm.) no definite evidence of compositional zoning could be found - however, this conclusion is less secure than in the case of the feldspars. The banding illustrated in Plate 2-9, is interpreted as being due to crystal settling; however, due to both uralitisation and recrystallisation petrographic examination throws no further light on this point.

The possible significance of these points will be discussed in the next chapter.

CHAPTER 6

A PETROGENETIC HYPOTHESIS FOR THE WHITESTONE ANORTHOSITE

6a. Introduction

The preceding chapters, while largely descriptive, have incorporated interpretive conclusions, but only on specific, subsidiary topics. In the present chapter a tentative petrogenetic model for the Whitestone anorthosite will be presented, such model being based on the observations and inductions of the foregoing chapters and on the whole rock analyses of 35 specimens distributed as on fig. 6-1. However, several controversial aspects of the chemistry and crystallisation of anorthosites require preliminary discussion.

For example, the standing of anorthosites vis-a-vis magma-type[1] is by no means clear. Buddington (1939,1961) has suggested that anorthosites represent a distinct magma-type of the composition of gabbroic anorthosite; Bridgewater (1967) proposes they are of the alkali stem of the Gardar province: Philpotts (1966) advocates a calc-alkali lineage (the mangerites being the acid differentiates); such an origin was suggested by Kranck (1961), following a suggestion by Osborne (1936), when he proposed that the anorthosites of the eastern Canadian Shield are the deep-seated equivalents of the calc-alkali batholiths of the western Cordillera[2]. The

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[1] As defined by Bailey E.B. & others (1924); Tertiary & Post-Tertiary Geology of Mull, Loch Aline and Oban: Geol. Surv. Scot. Mem.

[2] Emslie who initially, (1965), proposed a parental olivine basalt magma now, (1969), appears to have entered this camp agreeing that juxtaposed syenites, adamellites etc. are cogenetic with all Canadian anorthosites.

bearing of the chemistry of the Whitestone body on this point will be discussed.

Inextricably bound up with this is the crystallisation history of the anorthosite. Do anorthosites represent crystallisation from a unique magma-type or are they cumulate-rocks from a magma of some other, more 'normal', composition, or is assimilation important in their genesis? The light the present data throws on this feature will be discussed.

The genesis of the Fe-Ti-oxides, almost invariably associated with massif-anorthosites will also be examined. Hargraves (1962) and Philpotts A. (1967) have both suggested that these ores have crystallised from a distinct melt which has separated from, and is immiscible in, the magma from which the other phases have crystallised.

6b. Magma-Type: Introduction

Acidic rocks usually present no difficulties regarding their assignation to magma-type but more basic varieties are often controversial unless there is clear geologic evidence linking them with their descendants, as for example, in a layered intrusion. Volcanologists, in whose field the problem is particularly acute, have devised several schemes based on chemical analyses. Yoder & Tilley (1962) have proposed a 5-fold classification based on normative hyperstheme.

1) Tholeiite (oversaturated): norm Hy + Q
2) Tholeiite (saturated): norm Hy
3) Olivine Tholeiite (undersaturated): norm Hy + Ol
4) Olivine Basalt: norm Ol
5) Alkali Basalt: norm Ol + Ne

However, McDonald & Katsura (1964) have noted that normative Hy is dependent on the Fe oxidation state which, as analysed, may not be primary and they have forwarded a two-fold classification into tholeiites and alkali basalts on the basis of the ratio alkaliis/silica.

$$\begin{aligned} SiO_2 &> 39 + 2.7 \text{ Alk.} \text{ --- Tholeiitic} \\ SiO_2 &< 39 + 2.7 \text{ Alk.} \text{ --- Alkalic} \end{aligned}$$

Chayes (1966), who denigrates the designation tholeiite as being of bastardly lineage (even implying miscegenation), proposes a two-fold classification into alkaline and sub-alkaline (= tholeiites) identical with (1 + 2) and (4 + 5) of Yoder & Tilley respectively, with the latter's group 3 (i.e. rocks in which $Q + Ne = 0$) split between the two on the basis of a linear and quadratic discrimination function.

Table 6-1 lists the C.I.P.W. norms for 35 Whitestone rocks[1], located as in fig. 6-1, and Table 6-2 lists the taxonomic result on applying the three sets of criteria given above. Although there is some divergence all agree that the majority are of a tholeiitic cast. However, implicit in these schemes is that the rock analysis is representative of the composition of the magma - for magmas subject to crystal fractionation this will only hold for the chilled contact rocks (if available).

6c. Crystallisation History: Introduction

There is virtually no explicit discussion of the crystallisation of anorthosites in the literature although several workers (e.g. Buddington (1939), Emslie (1965), Philpotts (1966) and Romey (1967)) allude to specific aspects. Particularly important is whether crystal-sorting has

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[1] Molecular norms in Table A-8 (Appendix).

TABLE 6-1

C.I.P.W. Norms for Anorthosites

Lab No	Q	Ne	Feld			Cpx			Opx		Ol		Mt	Il	Others
			Or	Ab	An	Wo	En	Fs	En	Fs	Fo	Fa			
90	2.1	*	3.6	28.2	41.4	4.4	1.9	2.5	4.5	5.8	*	*	2.5	2.7	0.2^A
105	0.7	*	3.3	33.3	58.2	0.7	0.5	0.1	1.6	0.4	*	*	1.0	0.3	0.0^A
106	*	1.2	2.5	16.2	62.3	7.8	5.2	2.0	*	*	0.6	0.2	1.3	0.6	0.1^A
107	*	1.3	1.2	12.9	45.0	18.7	12.8	4.5	*	*	0.3	0.1	2.2	1.0	0.1^A
140	*	1.1	3.6	33.0	40.8	5.6	3.4	2.0	*	*	4.7	3.0	2.0	0.8	0.1^A
142	0.3	*	2.8	33.1	52.0	2.9	1.9	0.8	3.2	1.4	*	*	1.1	0.4	0.1^A
336	5.1	*	3.3	28.7	45.8	3.2	2.0	1.1	4.3	2.3	*	*	2.9	1.2	0.2^A
2	4.6	*	5.5	27.4	39.3	4.0	1.7	2.4	3.3	4.7	*	*	4.2	2.9	
13	3.1	*	3.3	34.3	41.8	2.7	1.2	1.5	3.8	4.6	*	*	1.9	1.8	
17	3.9	*	4.8	30.7	41.8	5.6	2.8	2.6	2.4	2.3	*	*	1.6	1.4	
20	1.5	*	3.1	33.3	43.7	3.6	1.4	2.3	2.6	4.2	*	*	2.2	2.2	
24	1.3	*	2.3	26.2	43.1	3.0	1.5	1.5	6.3	6.7	*	*	4.7	3.3	
30	1.6	*	2.6	32.6	57.0	0.4	0.2	0.2	2.3	1.6	*	*	0.9	0.5	
79	*	1.0	4.2	32.2	42.2	8.6	5.1	3.1	*	*	0.8	0.5	1.6	0.7	
134	0.6	*	2.7	33.3	55.2	1.0	0.6	0.4	2.9	2.0	*	*	1.0	0.5	
144	*	0.2	3.6	34.1	56.3	1.5	1.1	0.4	*	*	1.1	0.4	0.9	0.3	
168	*	1.0	3.4	30.6	46.3	8.3	5.4	2.4	*	*	*	*	1.7	0.8	0.3^1
181	1.3	*	2.2	35.6	58.8	0.8	0.6	0.1	0.1	*	*	*	0.4	0.2	
206	*	*	2.1	32.7	48.2	3.6	1.4	2.3	0.4	0.7	1.5	2.8	2.2	2.0	
213	1.2	*	2.6	34.7	59.3	*	*	*	0.9	0.2	*	*	0.7	0.2	0.4^2
214	0.2	*	2.6	28.2	49.7	7.1	5.0	1.5	2.2	0.7	*	*	2.1	0.8	
218	*	*	2.3	34.2	26.6	3.0	1.9	0.9	*	*	0.1	0.0	0.7	0.3	
222	0.9	*	2.8	31.1	41.9	5.5	2.7	2.7	3.4	3.4	*	*	1.8	3.8	
241	*	*	3.0	33.9	51.7	4.2	2.4	1.6	0.5	0.4	0.1	0.1	1.5	0.8	
246	1.1	*	3.2	28.7	46.4	4.1	2.1	1.8	4.4	3.7	*	*	2.4	1.9	
250	*	1.3	3.3	30.3	49.5	4.7	2.4	2.2	*	*	2.1	2.1	1.2	0.9	
260	0.1	*	1.4	31.8	56.2	1.1	0.7	0.4	4.5	2.4	*	*	1.0	0.4	
261	*	*	2.5	37.2	57.1	1.1	0.7	0.3	*	*	0.4	0.2	0.4	0.2	
274	1.1	*	1.7	31.4	55.6	1.9	1.2	0.6	3.6	1.6	*	*	1.0	0.3	
283	*	0.4	2.9	32.2	49.5	5.9	3.8	1.7	*	*	0.9	0.4	1.5	0.7	
297	*	0.3	1.7	31.7	54.6	4.5	3.1	1.2	*	*	1.1	0.4	1.0	0.4	
344	5.9	*	4.0	31.0	35.8	5.9	2.7	3.1	2.4	2.8	*	*	3.3	3.0	
352	0.3	*	2.8	31.8	53.1	3.6	2.5	0.8	2.7	0.8	*	*	1.2	0.3	
357	2.7	*	5.5	32.2	46.8	2.0	1.0	0.9	3.2	2.8	*	*	1.7	1.2	
372	1.9	*	4.8	31.1	52.7	1.2	0.7	0.4	3.1	1.7	*	*	1.6	0.8	
376	1.2	*	4.5	32.5	51.8	1.4	0.7	0.7	2.0	2.1	*	*	2.0	1.3	

A = Apatite　　1 = Wollastonite　　2 = Corundum

TABLE 6-2

Classification by Norm

McD & K	Lab No	Y & T	Chayes
Alkaline	79	Group 5	Alkaline
	140		
	250		
Tholeiitic	106		
	107		
	144		
	283		
	297		
	218	Group 4	
	261		
	206	Group 3	
	241		
	2	Group 1	Sub-alkaline
	13		
	17		
	20		
	24		
	30		
	134		
	181		
	213		
	214		
	222		
	246		
	260		
	274		
	344		
	352		
	357		
	372		
	376		

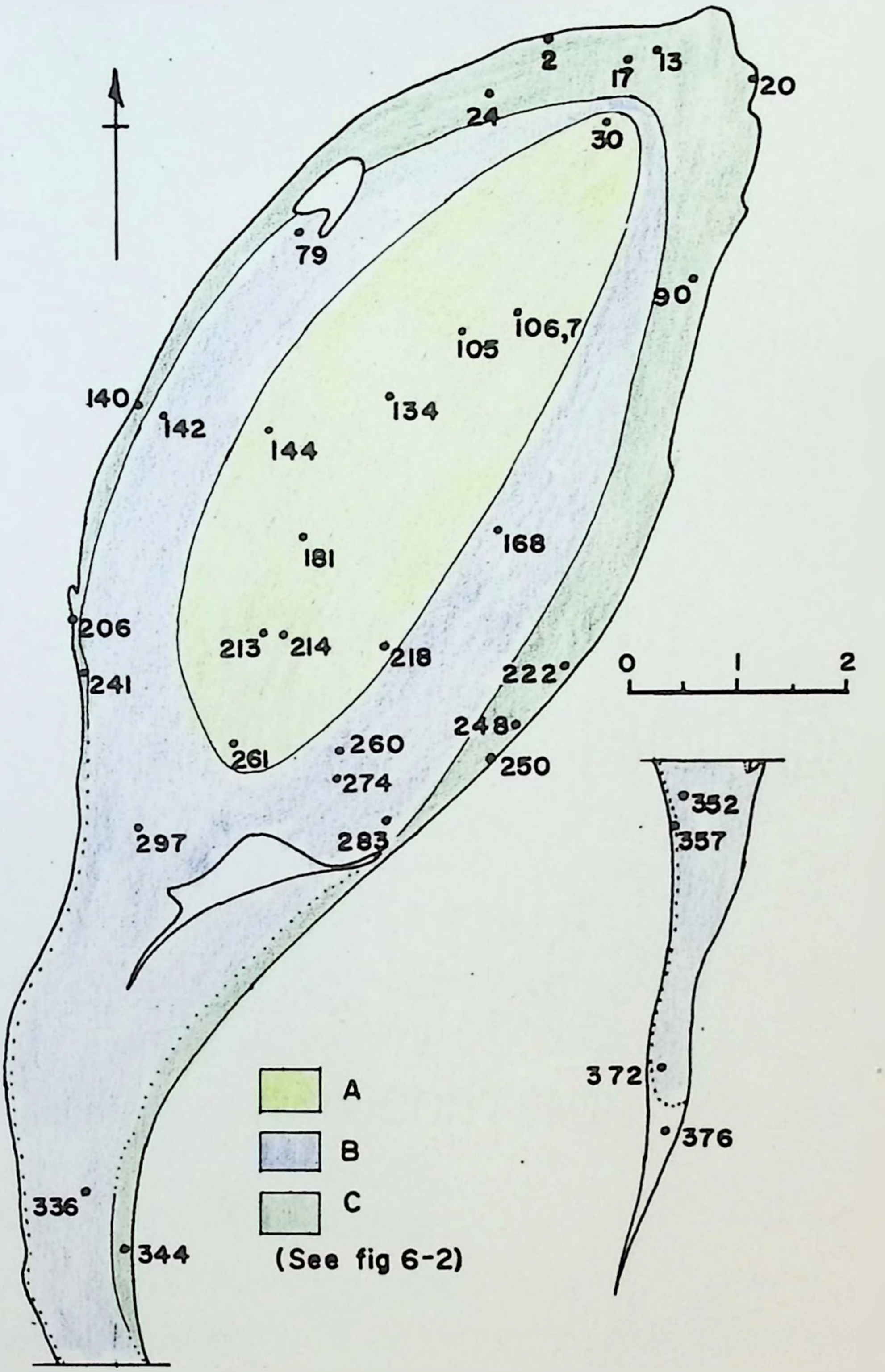

FIG. 6-1 Distribution of analysed rocks.

played a role in the genesis of anorthosites.

According to Hess (1960) trends plotted on an AFM diagram distinguish between magmas which have crystallised with extreme fractional crystallisation (e.g. Skaergaard) and those in which this process was less important (e.g. Garabal Hill calc-alkaline rocks and volcanic rocks). Papezik (1965, fig. 7) has plotted 44 analyses of the Morin anorthosite on such a diagram and proposes that the 'Mauve facies' of this anorthosite shows iron-enrichment during crystallisation, similar to the Skaergaard. The Whitestone analyses plot on the AFM diagram, fig. 6-2, with a distribution essentially similar to the Morin rocks. Neither in this diagram nor an equivalent one for the Morin is there a complementary MgO trending limb which would make Papezik's conclusion more credible. Further, it is noted that in such bodies as the Skaergaard (Wager 1960) and the Red Hill intrusion (McDougall 1962) the alkali-rich analyses and, for that matter, the Fe-rich ones, represent only a few % of the complete body - not the vast bulk as in the case of anorthosites.

In fig. 6-2bthere appears to be three distinct 'trends' (labelled A, B and C) and, when locales of rocks falling on each trend are plotted on a map of the pluton, it is noted that A, B and C types define three distinct areas of the anorthosite - see fig. 6-1. Trend A, characterised by increasing alkalies at a constant F/M ratio[1], I interpret as representing rocks with differing amounts of modal plagioclase and therefore not of significance for present purposes. 'Trend' (in fact-area) C, I interpret as rocks to which varying amounts of FeO (in the form of oxides) have

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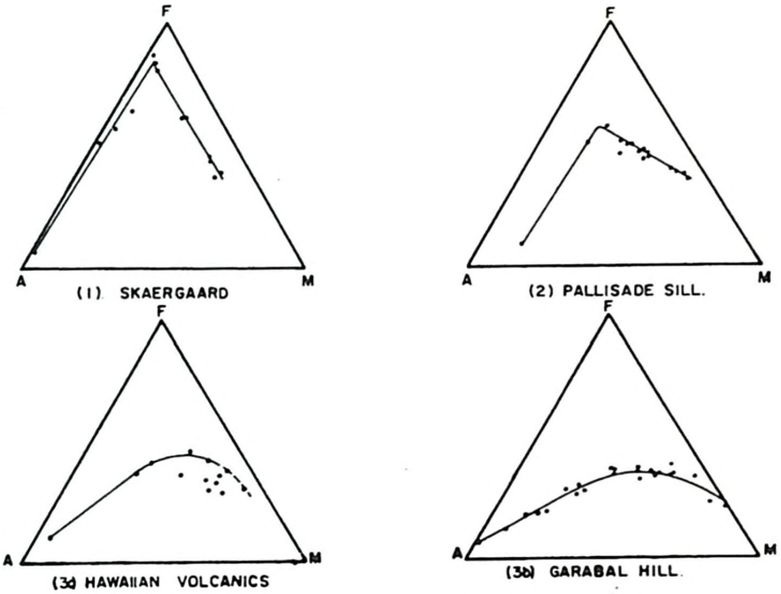
[1] Note that 357 and 376, occurring close to the margins in the tail of the pluton, contain atypically large amounts of mica. Potassium contamination from the country rock is suspected.



(1) SKAERGAARD

(2) PALLISADE SILL.

(3a) HAWAIIAN VOLCANICS

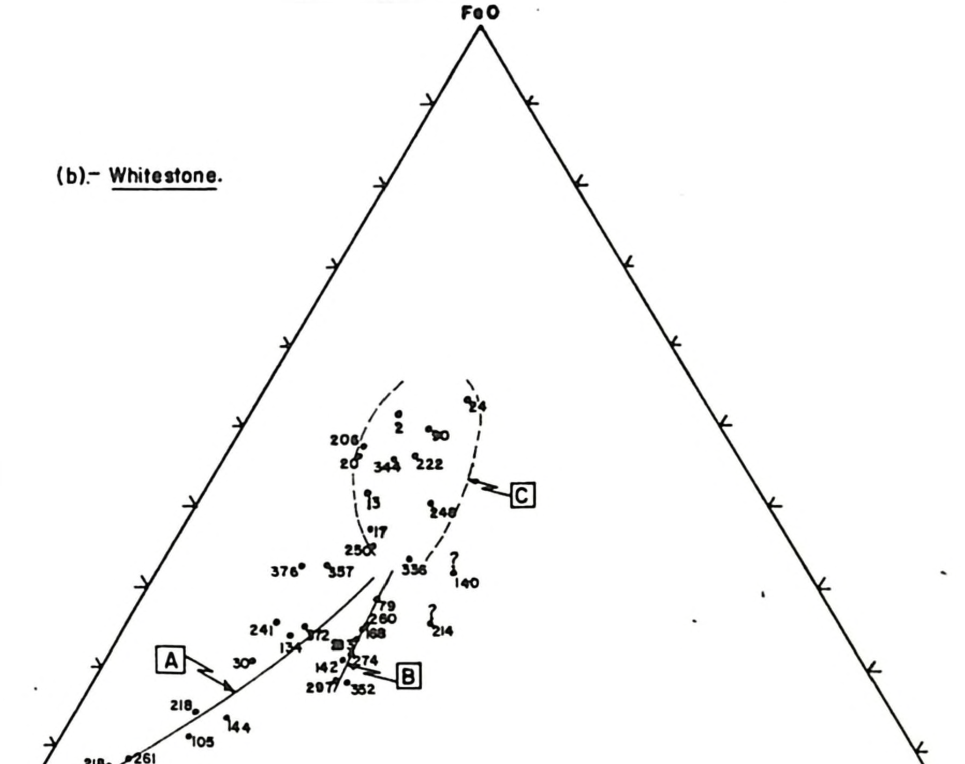
(3b) GARABAL HILL.

(a)- Differentiation trends with decreasing amounts of fractionation.

(After Hess, 1960.)

FIG-6-2 PLOTS OF MgO, FeO, $Na_2O + K_2O$; (Wt. %).

(b).- Whitestone.



been added: the correlation of the distribution of C-type analyses with oxide distribution is pointed out - (cf. fig. 6-1 and fig. 5-9). Although it is perhaps the best defined (although the shortest) the significance of trend B is not entirely clear at the moment. It indicates an increasing F/M ratio accompanied by decreasing alkalies which could perhaps be rationalised on a model supposing that the mafic minerals are becoming more Fe-rich and, simultaneously, more modally abundant. However, more analytical data is required before leaning on this feature too heavily.

Although apparently satisfactory for many rock types I do not believe the AFM plot does justice to the analyses of anorthosites.

Another conventionally used diagram for fractionated rocks is the plot of Mafic Index vs. Felsic Index[1] which, according to Simpson (1954), illustrates the relative importance of fractionation in the mafic and felsic minerals[2]. Fig. 6-3 shows that the Whitestone trend is superficially similar to the early and middle stages of the strongly fractionated Skaergaard and Black Jack bodies. However, as fig. 6-4 verifies, for the Skaergaard this initial increase in the Mafic Index can be correlated with an increasing Fe content of the pyroxenes - (olivines in the case of the Black Jack sill). The anorthositic clinopyroxenes do not show an equivalent Fe enrichment. In fact those rocks with a high Mafic Index are those lying in area C in fig. 6-2b - i.e. those enriched in oxide

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[1] Mafic Index $= \dfrac{(FeO+Fe_2O_3+MnO) \times 100}{FeO+Fe_2O_3+MnO+MgO}$ Felsic Index $= \dfrac{(Na_2O+K_2O) \times 100}{Na_2O+K_2O+CaO}$

[2] E.g. in the Skaergaard fig. 6-3 illustrates that in the early and middle stages differentiation is controlled by fractionation of the mafic minerals while in the late stages increase in alkalies of the feldspars become prominent. In Daly's calc alkaline series neither predominates.

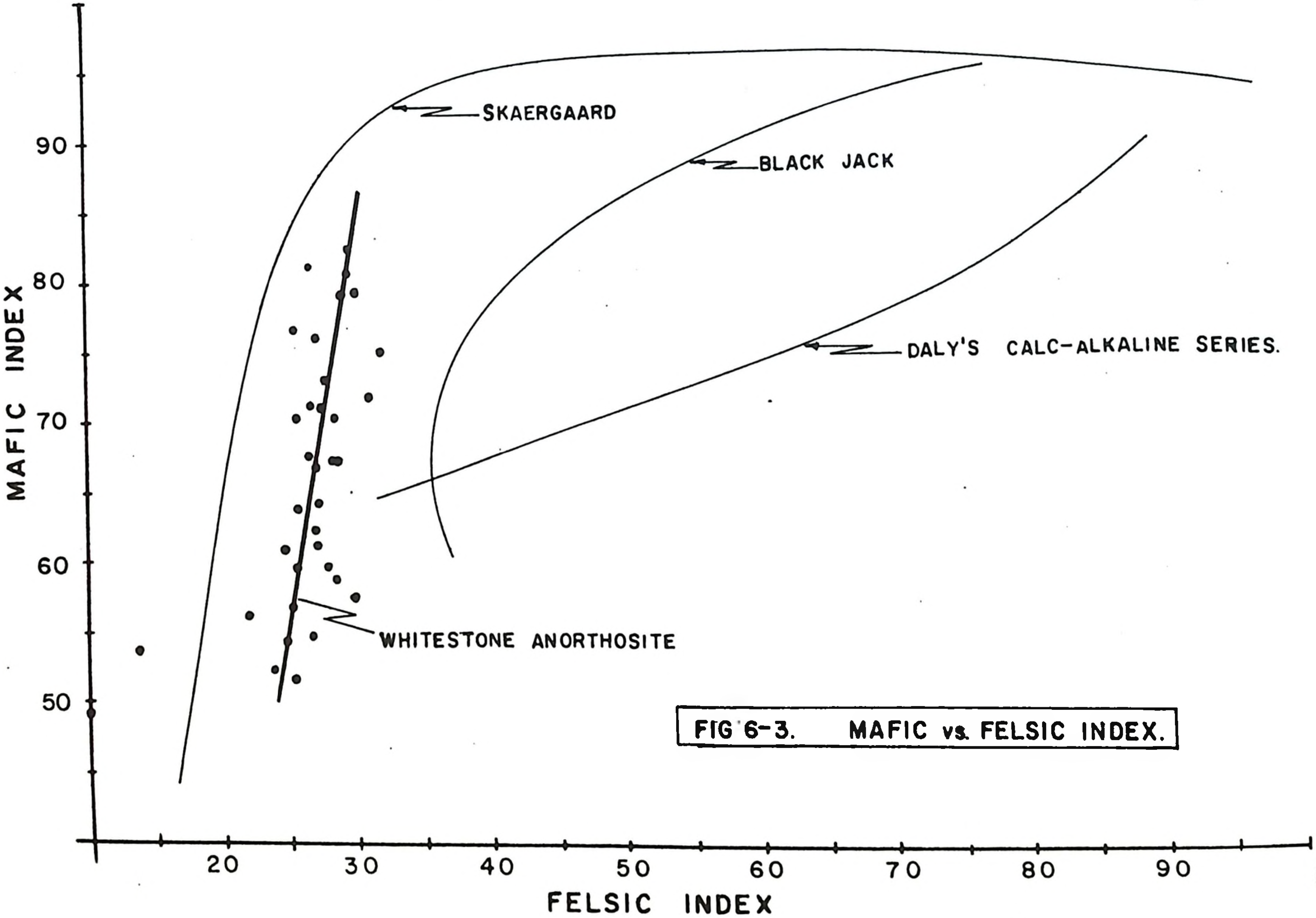

FIG 6-3. MAFIC vs. FELSIC INDEX.

minerals.

In summary then, the features of the Whitestone anorthosite are not responsive to conventional diagrammatic techniques for classification.

6d. Pyroxenes and Magmas

Wilkinson (1956) has noted that a chemical distinction can be drawn between the clinopyroxenes of tholeiitic and alkalic intrusives. Table 6-3 lists these differences along with several contrasting paragenetic features while fig. 6-4a and b illustrates some of these features for the Skaergaard and Garbh Eilean intrusions - representing tholeiitic (high alumina) and mildly alkaline[1] respectively. It will be recalled that in the Skaergaard the early clinopyroxenes coexist with a Ca-poor pyroxene and only in the later stages does a fayalitic olivine appear, apparently coinciding with the disappearance of pigeonite. For the Garbh Eilean sill olivine coexists with the clinopyroxene to the exclusion of orthopyroxene and pigeonite. In the former case the increasing Fe/Mg ratio of the rock is correlated with the increasing Fe/Mg ratio of the clinopyroxene (+ orthopyroxene and fayalite) while in the latter the increasing Fe/Mg ratio of the rock is due largely to increasing Fe/Mg ratio of the olivine alone. It follows therefore that, barring any drastic, secondary effects, the nature[2] of the clinopyroxene may be of prime petrogenetic significance particularly in that it is independent of the bulk analysis of the rock in which it occurs.

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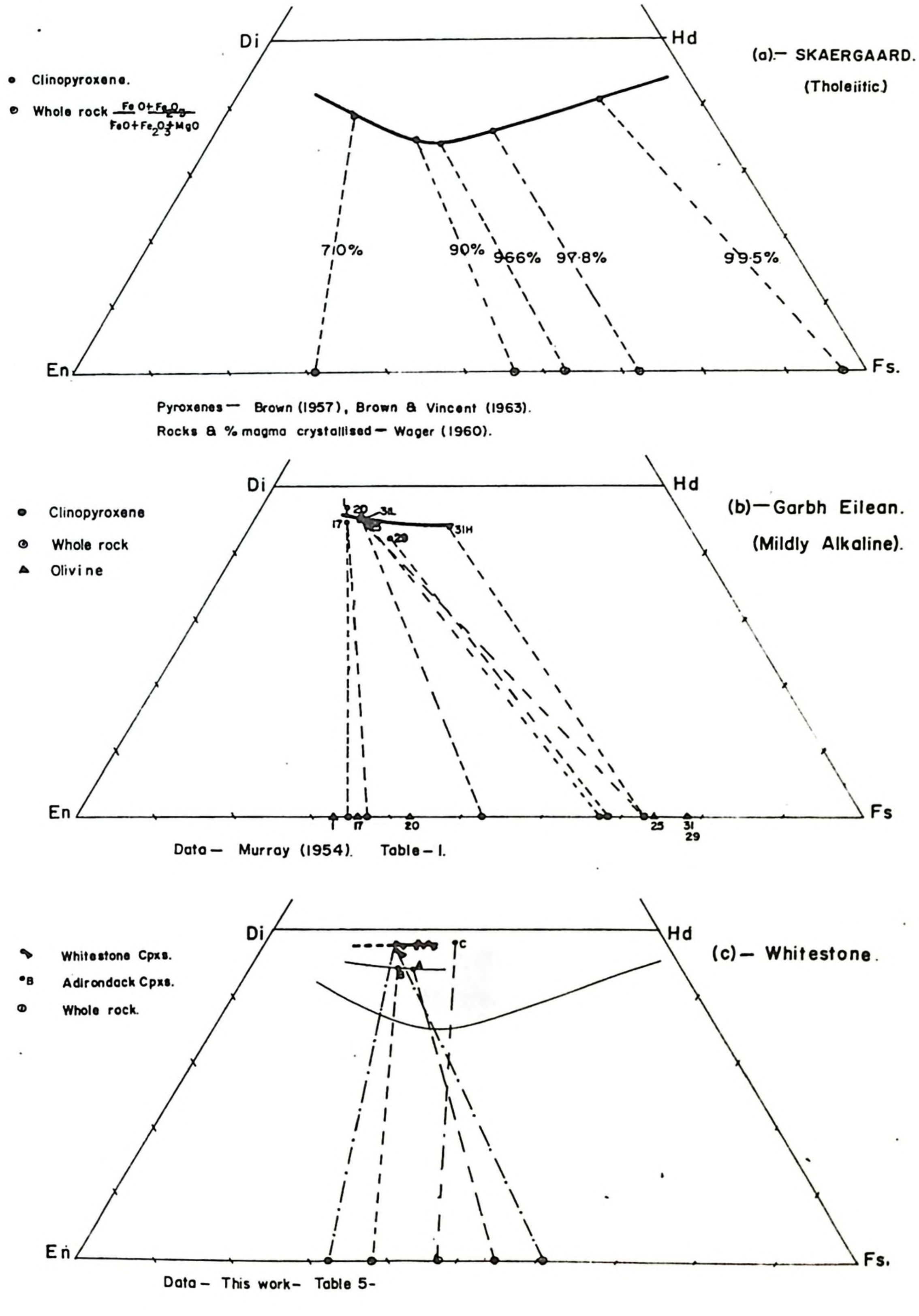
[1] For strongly alkaline intrusions (of agpaitic type) the pyroxenes are usually very rich in the acmite molecule and cannot be conveniently represented on this plot.

[2] Included in 'nature' are both specific and serial features.

TABLE 6-3

Contrasted Properties of Clinopyroxenes from Tholeiitic and Alkalic Intrusions

Tholeiitic Clinopyroxenes	Alkalic Clinopyroxenes
Augitic in CaO content. CaO varies regularly with differentiation.	Diopsidic in CaO content. CaO content relatively constant.
During differentiation shows considerable enrichment in Hd molecule. No tendency to aegirine.	During differentiation shows limited enrichment in Hd molecule. In per-alkaline rocks diopsidic cpx. may be replaced by aegirine.
Usually accompanied by an orthopyroxene or pigeonite depending on composition. Similarly, cpx. often has exsolution lamellae of Ca-poor phase, and coexisting Ca-poor phase usually has exsolution of cpx.	Usually accompanied by olivine. Opx. both as exsolution lamellae and coexisting phase generally absent.
	Generally richer than tholeiitic cpx. in TiO_2, Al_2O_3, Fe_2O_3 and (especially in per-alkaline) Na_2O.



(a):— SKAERGAARD.
(Tholeiitic)

Pyroxenes— Brown (1957), Brown & Vincent (1963).
Rocks & % magma crystallised— Wager (1960).

(b)—Garbh Eilean.
(Mildly Alkaline).

Data— Murray (1954). Table-1.

(c)— Whitestone.

Data— This work— Table 5-

FIG. 6-4. Differentiation of clinopyroxenes.

(Plotted as $Ca+Mg+\Sigma Fe = 100$ atom %)

Unfortunately the phase relations in the pyroxene quadrilateral[1] have not yet been fully determined so that it is not yet possible to categorically state whether such differences are due to chemical or physical parameters. Because of their general applicability to rocks of known tholeiitic and alkalic affinities it is intuitively reasonable that most of the differences listed in Table 6-3 are chemically controlled. Preliminary work on the pyroxene quadrilateral liquidus, Roedder (1965) and Turnock (unpublished preliminary work), indicates a (shallow?) minimum which may lie between the Skaergaard and Garbh Eilean trends so that, e.g., the presence or absence of a Ca poor pyroxene phase would be chemically controlled. However, in the case of degree of Fe-enrichment Wilkinson (1957), Le Maitre (1962) and Deer & Abbot (1965) have all essentially argued that a high P_{H_2O} is equivalent to a high P_{O_2} which results in a high Fe^{+3}/Fe^{+2} therefore allowing only limited Fe-enrichment in the clinopyroxene. However, on the balance, it seems that the majority of the points noted in Table 6-3 are chemically controlled.

Fig. 6-4c at first sight shows a distinct similarity to the alkalic pyroxenes (fig. 6-4b) in (a) being diopsidic, (b) showing limited Fe-enrichment and (c) showing lack of correlation between Fe/Mg ratio of pyroxene and whole rock. However, significant contrasts remain. While item (c) in alkalic whole rock is compensated for by increasing Fe/Mg ratio of the coexisting olivines, this is not the case in anorthosites. As noted above the Fe-enrichment of anorthosites is compelled by the Fe/Ti-oxides - not the silicate minerals. This raises the possibility

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[1] i.e. in terms of the four end-members Diopside, Enstatite, Hedenbergite and Ferrosilite. Alkalic pyroxenes are not considered in the present discussion.

that the P_{O_2} controls the fractionation history so that apparent trends must be treated with caution.

In this regard it is recalled that the other pyroxenes culled from the literature showing orientated oxide exsolution (viz. the Kap Edvard Holm (K.E.H.) and the Guadaloupe complexes) both show a notable lack of Fe-enrichment and both are diopsidic rather than augitic in composition. Deer & Abbot (1965) believe the K.E.H. magma to be similar to that of the Skaergaard and Best (1967) takes the Guadaloupe rocks to be part of the southern Californian calc-alkaline series (usually reckoned to be broadly tholeiitic). In both cases the authors appeal to a high P_{H_2O} to explain the pyroxene fractionation, though in different ways. The K.E.H. pyroxenes are accompanied throughout most of their history by olivine but olivine is only present in the very earliest of the Guadaloupe rocks.

Sidestepping this issue for the present, the significance of structurally significant components ignored in the projection used in fig. 6-4 is emphasised. For example, Kushiro (1960) and Le Bas (1962) have indicated that Al and Ti are significant. Both use plots of Si vs. Al and Al vs. Ti, in effect ignoring MgO, FeO and CaO used in fig. 6-4. In an attempt to achieve a more comprehensive analysis of the pyroxene composition a recalculation procedure outlined in Table 6-4 can be used.

Notes on Recalculation

In this scheme the pyroxene analysis is recalculated into the theoretical end-members Acmite (Jadeite), total Tschermakite (i.e. Mg+Ca), Diopside, Hedenbergite and Enstatite in a manner essentially similar to that of Yoder & Tilley (1962) p. 366-7. Since the aim is to reveal overall chemical differences and similarities of individual clinopyroxenes rather than the differentiation history certain simplifying liberties are taken. For example, no attempt is made to retain the appropriate Fe/Mg ratio in the calculation and any Ca-free pyroxene is calculated as pure

TABLE 6-4

Recalculation of a Pyroxene Analysis
(see Yoder & Tilley 1962, p. 366-7 for further details)

Skaergaard Clinopyroxene, Brown (1957) Table 1, No. 3

(a) Structural Formula on Basis of 6 Oxygens

Ca	Na	K	Mg	Fe^{+2}	Fe^{+3}	Ti	Al^6	Al^4	Si
.759	.027	.002	.833	.284	.047	.022	.030	.097	1.904

(b) Rearrangement on Basis of 400 Cations and Recalculation.

	X=100			Y=100					Z=200		
	Ca_{76}	Na_3	Mg_{21}	Mg_{62}	Fe^{+2}_{28}	Fe^{+3}_5	Ti_2	Al_3	Al_{10}	Si_{190}	
Ac		Na_3				Fe^{+3}_3				Si_6	Ac_3
Jd		—				—					Jd_0
Ts			Mg_{10}	Mg_3		Fe^{+3}_2	Ti_2	Al_3	Al_{10}	Si_{10}	Ts_{10}*
En			Mg_{11}	Mg_{11}						Si_{22}	En_{11}
Di	Ca_{48}			Mg_{48}						Si_{96}	Di_{48}
Hd	Ca_{28}				Fe^{+2}_{28}					Si_{56}	Hd_{28}

*Composition Ts $= Mg_{100}(Mg_{30}Fe^{+3}_{20}Ti_{20}Al_{30})AlSi$

Notes

1) Since chemical analyses rarely reduce to a complete structural formula some judgement must be exercised in rearrangement in step (b). It is recommended that only analyses in which X+Y in the structural formula $= 2.00 \pm 0.02$ should be used - otherwise rearrangement becomes extravagantly arbitrary.

2) Perhaps because of the rather arbitrary rearrangement and original chemical inaccuracies it is not always possible to have the charges in the Ts molecule balance.

enstatite[1]. In effect this is equivalent to recalculating in terms of triangle Di:Hd:En instead of quadrilateral Di:Hd:Fs:En so that it is not appropriate for pyroxenes near the Hd:Fs sideline. Such arbitrary procedures reduce the calculation to a very rapid and simple process (with practice, about as fast as the appropriate data card could be punched).

Table 6-5 lists some recalculated clinopyroxenes from mildly-alkaline rocks, tholeiites[2], anorthosites, the K.E.H. and Guadaloupe complex. In interpreting these results it is emphasised that both the amount of the Ts molecule and its composition are considered significant. In effect the amount of Ts molecule reflects the amount of Al in tetrahedral co-ordination (Al_4) while the composition of the Ts molecule reflects the relative importance of Al in octahedral co-ordination (Al_6). Table 6-6, listing the averages for the several groups, illustrates the essential distinctions to be made[1]. The tholeiitic clinopyroxenes can be distinguished immediately by virtue of their relatively large En and low Ts content - Table 6-6a. This reflects that such pyroxenes lie towards the centre of the pyroxene quadrilateral (cf. fig. 6-4). As in fig. 6-4, Table 6-6a indicates similarity between the clinopyroxenes from anorthosites and mildly alkaline rocks. However, in Table 6-6b the very high (Al_6) of the former distinguishes them from the alkalic variety indicating this feature may be of diagnostic value.

6d(i) The Role of Al in Clinopyroxenes

Experimental data bearing on the role of Al in clinopyroxenes is embodied in the work of Segnit (1953,1956), Clark, Schairer & de Neufville

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[1] With the aid of J. Coward a computer programme which plots these results in a stereoscopic tetrahedron has been prepared but, due to reproduction difficulties, has not been used.

[2] High alumina.

TABLE 6-5(a)

Alkalic Rocks Mildly undersaturated - more undersaturated rocks tend to differentiate towards acmitic pyroxenes (apparently with immiscibility-field between diopsides and acmites).

	Ac+Jd	Ts	Di	Hd	En	
I	3	15	65	17	-	
17	3	14	67	16	-	
20	3	15	63	19	-	Garbh Eilean numbered as in Murray (1954)
25	3	11	54	31	1	
29	1	13	45	35	6	
	5	24	50	31	-	Black Jack; Wilkinson (1957)
	5	16	47	32	-	
1)	5	24	56	15	-	
2)	6	21	57	16	-	Square Top; Wilkinson (1966)
5)	13	9	62	16	-	

Tschermaks Molecules

	Ca	Mg	Mg	Fe^{+3}	Ti	Al
I	73	27	66	13	22	0
17	71	29	78	8	14	0
20	27	73	40	27	27	6
25	-	100	28	18	36	18
29	-	100	15	38	30	17
	79	21	50	-	38	12
	56	44	46	-	38	16
1)	63	37	30	12	25	33
2)	57	43	33	14	29	24
5)	67	33	33	33	23	11

TABLE 6-5(b)

Tholeiites

No	Ac Jd	Ts	Di	Hd	En or Fs	Reference
1)	5	12	67	14	2	Skaergaard Numbered as in Brown (1957) Table 1 and Brown & Vincent (1963) Table 1
3)	3	10	48	28	11	
4)	3	10	37	36	14	
5)	2	7	27	43	21	
7)	2	8	16	51	23	
9)	2	6	9	60	23	
11)	3	5	4	73	15	
15)	2	6	0	83	11	
3)	2	5	17	48	28	Tasmanian dolerite (McDougall 1961)

Tschermaks Molecule in Tholeiites

	Ca	Mg	Mg	Fe^{3}	Ti	Al
1)	-	100	75	-	25	-
3)	-	100	30	20	20	30
4)	-	100	50	10	30	10
5)	-	100	-	29	29	32
7)	-	100	13	37	25	25
9)	-	100	17	50	33	-
11)	-	100	20	-	60	20
3)	-	100	20	20	20	40

TABLE 6-5(c)

Anorthosites

	Ac+Jd	Ts	Di	Hd	En
52	6	16	53	25	-
90	6	12	56	26	-
107	5	16	55	24	-
278	6	17	49	28	-
282	6	19	48	27	-
A	7	11	48	31	3
B	4	11	54	29	2
C	5	18	43	34	-

Numbered as in Table 5-6 (This thesis)

Adirondacks - see Table 5-6

Tschermaks for Anorthosites

	Ca	Mg	Mg	Fe^{+3}	Ti	Al
52	56	43	-	25	12	63
90	34	66	8	8	8	76
107	56	43	7	13	13	67
278	65	35	24	12	12	52
282	63	37	-	21	21	58
A	-	100	-	9	-	91
B	-	100	-	18	9	73
C	50	50	-	22	6	72

TABLE 6-5(d)

Granulites

No	Act+Jd	Ts	Di	Hd	En	Reference
C-1	3	6	43	43	5	Binns (1965b) Australia
C-8	3	6	15	72	4	"
C-3	3	7	10	72	10	"
C-7	3	8	49	37	3	"
26	-	7	50	30	12	Eskola (1952) Lapland
4642A	4	8	37	43	6	Howie (1955) Madras
2270	8	6	62	24	-	" " Salem
2941	9	16	45	30	-	" " Salem
7286	4	9	49	35	3	" (1958) Sudan

Tschermaks Molecule

	X		Y			
	Ca	Mg	Mg	Fe^{+3}	Ti	Al
C-1	-	100	35	-	16	50
C-8	-	100	34	16	16	34
C-3	-	100	70	15	15	-
C-7	-	100	38	-	12	50
26	-	100	-	60	-	40
4642A	-	100	25	-	15	60
2270	-	100	84	-	16	-
2941	25	75	37	-	13	50
7286	-	100	11	44	12	33

TABLE 6-6

Average of Recalculated Pyroxenes of Table 6-5

(a) Average Recalculated Clinopyroxenes

	Ac+Jd	Tsch.	Di+Hd	En
Alkalic	4.7	16.2	78.4	0.7
Tholeiitic	2.5	7.7	73.4	16.4
Anorthositic	5.4	15.3	78.7	0.6
Granulitic	4.1	8.1	83.1	4.7
K.E.H.	3.3	13.6	81.0	2.1
Guadaloupe	2.3	6.0	85.0	6.7

(b) Average for Y group of Tsch. molecule in above

	% Tsch.	Mg	Fe^{+3}	Ti	Al
Alkalic	16.2	41.8	16.3	28.2	13.7
Tholeiitic	7.7	28.2	20.9	30.3	19.6
Anorthositic	15.3	4.9	16.0	10.1	69.0
Granulitic	8.1	37.0	15.0	12.8	35.2
K.E.H.	13.6	43.3	9.4	20.6	26.7
Guadaloupe	6.0	11.0	16.6	22.0	50.4

(1962), Hays (1966) and Kushiro & Yoder (1966). Segnit (1956) has shown that in the Join $CaSiO_3$-$MgSiO_3$-Al_2O_3 at 1 atmosphere diopside with up to 11% Al_2O_3 can crystallise as a homogeneous phase from liquids of appropriate composition - i.e. Al content is presumably controlled by liquid composition. On the other hand, Clark et al, Hays and Kushiro & Yoder indicate that for a fixed composition increasing pressure will (substantially-sic) increase the Al content of the pyroxene in the joins $CaMgSi_2O_6$-$CaAlSi_2O_8$-SiO_2, region of $CaAl_2SiO_6$ and $CaAlSi_2O_8$-$MgSiO_4$ respectively. In the result, work in the system CaO-MgO-Al_2O_3-SiO_2 at various pressures has been restricted to binary and a few ternary joins so that it is not yet possible to deduce (from purely experimental results) the relative efficacy of pressure and chemical composition of the magma in governing the Al content of the clinopyroxenes.

Le Bas (1962) has argued that (Al_4) in clinopyroxenes (i.e. amount of Ts-component) is a function of the Si saturation (a_{SiO_2}), not the Al content of the magma, supposing that the more the magma is undersaturated with Si the more Al will substitute for the Si. On the other hand he argues, partly from variation in cell parameters[1], that (Al_6) (i.e. relative amount of Al in Ts-molecule) is a function of load pressure. In substantial agreement with this, clinopyroxenes from metamorphic granulites, while tholeiitic in En and Ts, are significantly richer in (Al_6) than igneous tholeiites. However, the anorthositic clinopyroxenes are almost twice as high as the granulitic pyroxenes in both Ts itself and in the Al content of Ts. Since there is no reason to suppose that pressures much

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[1] Clark et al (1962) show decreasing volume of unit cell with increasing $CaAl_2SiO_6$ - their fig. 4.

higher than granulite facies prevailed during the crystallisation of the anorthosite (see chapter 4), I propose that the richness in both (Al_4) and (Al_6) exhibited by the pyroxenes reflect crystallisation from a magma unusually rich in alumina[1], the effect probably abetted by a granulite facies pressure regime. In effect, I propose a third type of clinopyroxene distinct from the established tholeiitic and alkalic types.

6e. Magma-Type: Discussion and Interpretation

In an earlier section it was discovered that the usual criteria were not satisfactory in categorically establishing the identity of the parent magma of the Whitestone anorthosite. As noted, an important preliminary fact to be established to serve as a premise for further discussion is whether the anorthosite represents a cumulate from a magma of some other composition (perhaps, but not necessarily, one of the conventional magma types), or whether the pluton, as mapped, represents the complete magma, in which case a new magma-type would be defined and the origin of this magma would arise as a problem.

If the anorthosite crystallised from a magma of some other composition then two possibilities are open.

(a) The anorthosite represents an initial, basic cumulate and the more acidic differentiates are present either as juxtaposed 'syenites' or, possibly, the residual magma has been filter pressed out and has consolidated elsewhere either as a pluton

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[1] Even richer in Al than the so-called high-alumina tholeiites (e.g. Skaergaard). In Table 6-6a and b note that Skaergaard pyroxenes are as rich, or richer, in (Al_4) and (Al_6) than average alkalic pyroxene.

or lavas. Such would appear to be the view of such modern workers as Philpotts (1966), Emslie (1965,69) and Bridgewater (1967).

(b) The anorthosite crystallised from a magma which is itself residual in origin; an ultrabasic cumulate rock representing the complementary fraction of the magma. In effect such a process, if reasonable, is an alternative way of deriving a gabbroic anorthosite magma and would, in certain respects, be indistinguishable from a gabbroic anorthosite magma derived directly from the mantle by partial fusion, as proposed by Buddington (1961) and Hargraves (1962) - see chapter 1. In either case, of course, crystal accumulation could be active during solidification as in theory (a).

I believe that a metasomatic aureole such as is present round the Whitestone anorthosite eloquently argues against theory (a). That is, I argue that if the anorthosite is merely a basic cumulate then a metasomatic fluid phase could not, or would not, develop. Similarly, as argued above, the composition of the pyroxenes are not easily envisaged as crystallates from a 'normal' basic magma: in fact they indicate a magma of rather unusual composition. Table 4-6 is an attempt to indicate from the observations of other workers that a metasomatic aureole may exist round most massif anorthosites. However, since this argument may be considered tenuous and since theory (a) is currently in vogue[1] it is worthy of further scrutiny. Of the advocates, Philpotts' paper (1966) is undoubtedly the

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[1] See e.g. Green (1966) who has used it as a basis for his experimental work.

most quantitative exposition.

In two areas in Quebec Philpotts traces a continuous gradation from anorthosite through noritic anorthosite and jotunite to mangerite (essentially a quartz-rich pyroxene syenite or granite). The crucial point, as Philpotts realised, is the relation of the noritic anorthosite to the mangerite and, although he admits the field relations are equivocal, he believes the suite has been derived from a single magma with the anorthosites representing cumulate rocks and the mangerites the acidic differentiates[1]. In particular Philpotts notes "The strongest evidence in favour of a co-magmatic origin ...... is the chemical variation of the rocks of this series." - p. 48. He chooses to illustrate the cohesion of this series by plotting wt% of individual oxides versus wt% (CaO+MgO) - his fig. 13. However, as can be shown by plotting patently non-co-magmatic rocks, the (CaO+MgO) parameter tends to give a relatively smooth curve for almost any rocks varying from basic to acidic - see fig. 6-5. Using as a slightly more sophisticated crystallisation parameter the crystallisation index of Poldervaart & Parker (1964), fig. 6-6 is obtained using the analyses of Table 4 in Philpotts (1966). In fig. 6-6 the evidence for a continuous chemical gradation is far from compelling. In point of fact it is, at the least, equally valid to interpret fig. 6-6 in the light of the conclusions of this thesis as follows. The more basic rocks (i.e. rocks with a high C.I.) show an iron enrichment trend and there is a separate, earlier, acidic magma (open symbols in fig. 6-6)

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[1] Because of the vast bulk of these putative differentiates relative to the basic fractions, compared to, say, the Skaergaard where they represent only a fraction of a %, he postulates a calc-alkaline magma derived from a tholeiitic magma which has assimilated vast quantities of country rock.

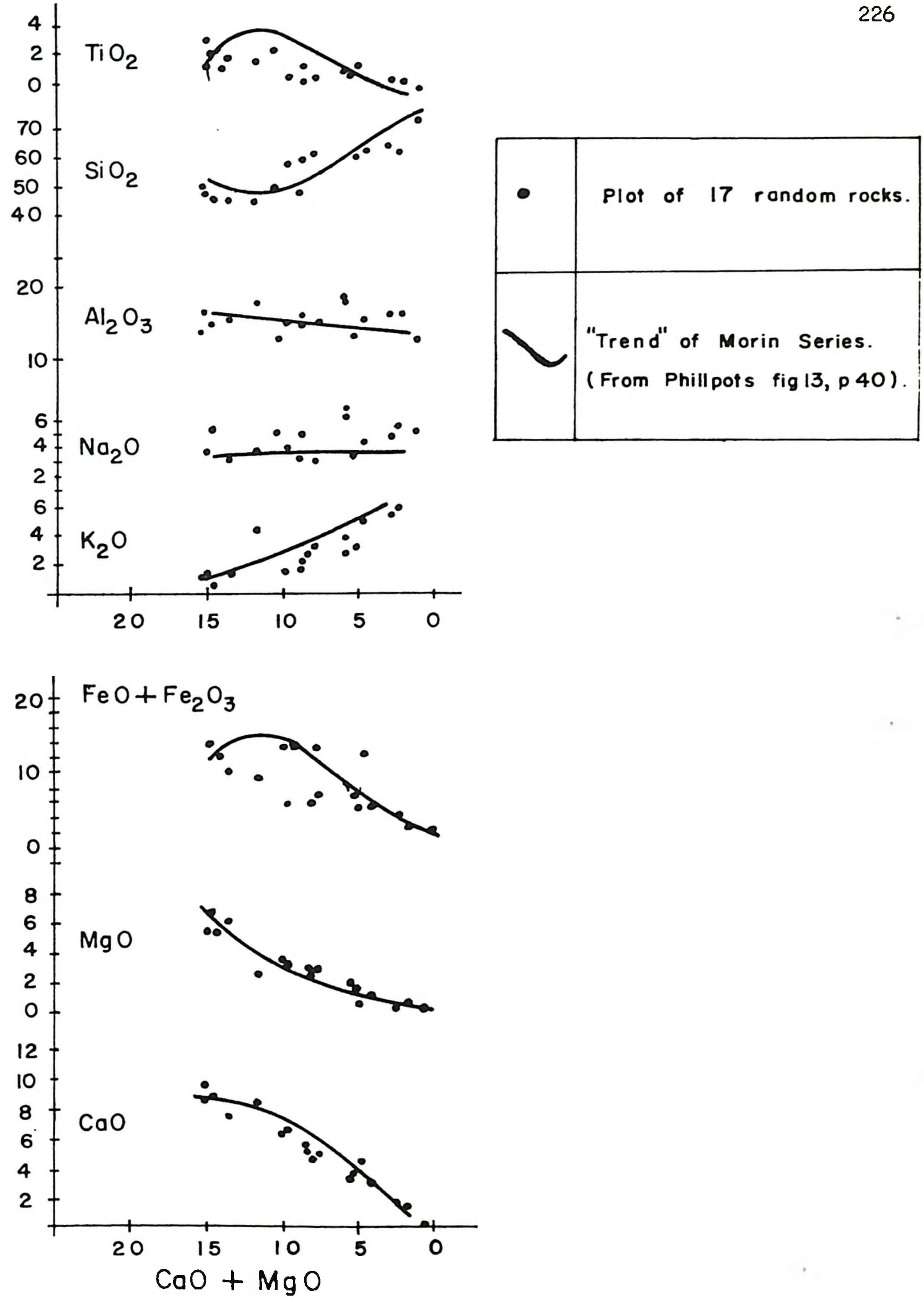

FIG. 6-5. Plot of oxides vs. CaO + MgO for non-cogenetic rocks given in Table 6-7

TABLE 6-7

Rocks plotted on Fig. 6-5

Average of quartz syenites of Bushveld (Mean of 5 analyses)	T & V[1], p.232, No.5
Quartz syenite of White Mt. (Mean of 2 analyses)	T & V, p.265, No.7
Tonalite; S. Calif. Batholith	T & V, p.272, No.1
Larvekite; Oslo, Norway (1)	T & V, p.272, No.10
Nordmarkite; Oslo, Norway (1)	T & V, p.272, No.9
Basalt; St. Helene (Mean of 4 analyses)	T & V, p.137, No.3
Leucite Tephrite (1)	T & V, p.134, No.6
Mugearite; Skye (1)	T & V, p.193, No.4
Tholeiite Basalt; Hebrides (Mean of 8 analyses)	T & V, p.193, No.7
Spilite; N.S.W.	T & V, p.204, No.2
Spilite; N.Z.	T & V, p.204, No.3
Quartz Keratophyre; N.Z.	T & V, p.204, No.6
Hypersthene Andesite; Crab Lake, Oregon	T & V, p.221, No.5
Quartz Syenite; Diana Complex (Weighted average composition)	T & V, p.272, No.8
Eclogite; New Caledonia	Coleman et al, p.489, No.6
Average Igneous Rock	Brotzen, p.867, No.3
Trachyte; Hawaii	McDonald & Katsura, p.121, No.27

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[1] Turner & Verhoogen

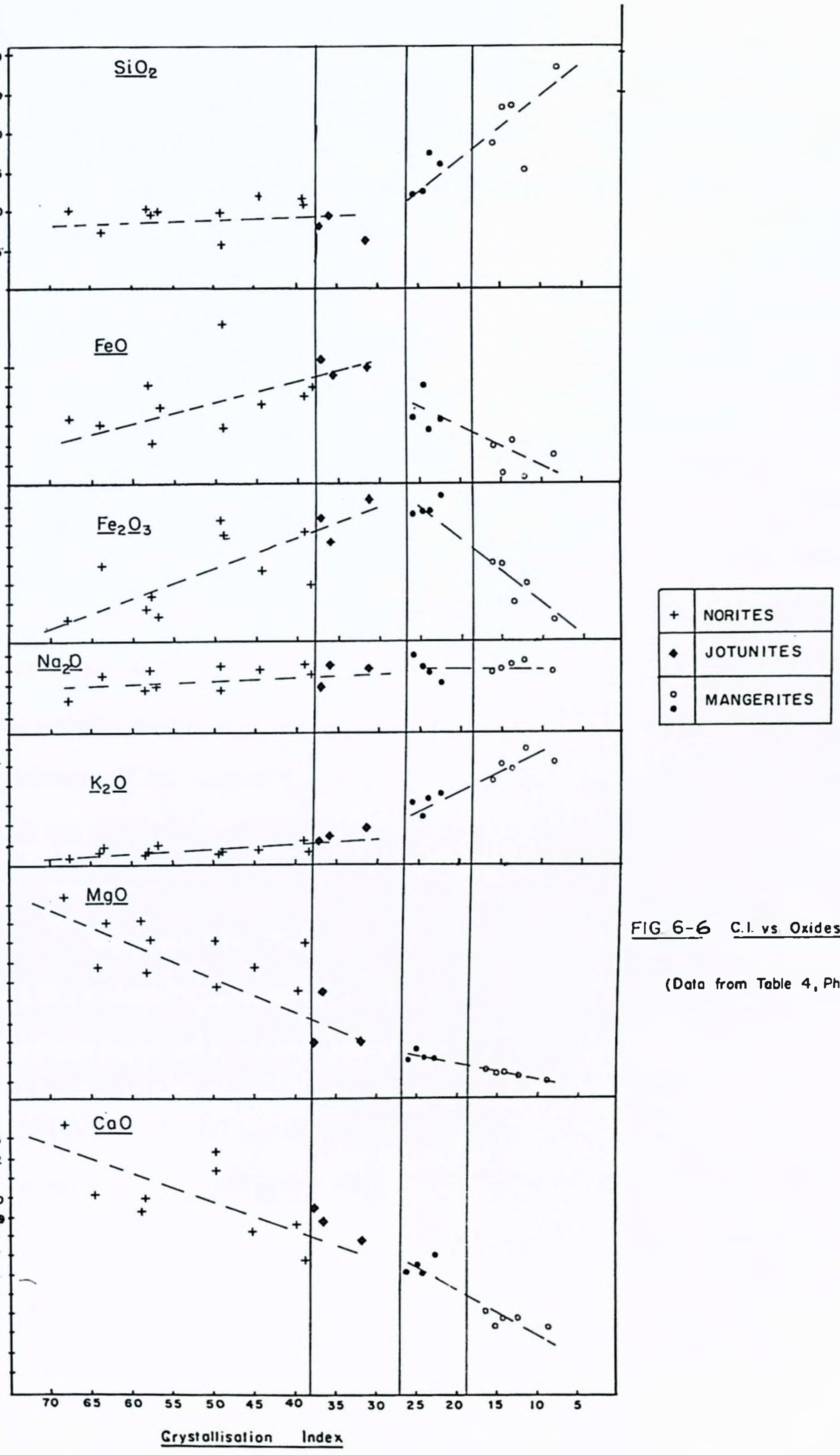

FIG 6-6 C.I. vs Oxides for "Morin" Rocks

(Data from Table 4, Philpotts 1966.)

which has been altered near the contact by the later basic magma (metasomatised?) to give rise to hybrid rocks (closed symbols). It is significant to recall that modes of these 'hybrid' rocks show 10-15% iron oxides (see Philpotts' Table 4).

A further difficulty with the cumulate theory is that in virtually all massif anorthosites the Fe-Ti ore is concentrated at the contact between the anorthositic and acidic rocks; the consistency of the locus of these ores requires an explanation that cannot be supplied easily by the cumulate theory. Moreover, while in many cases (e.g. Morin - Philpotts (1966), Adirondacks - Buddington (1939), Allard Lake - Hargraves (1962), Sept Isles - Faessler (1942) and Nain - Wheeler (1942,1960)) the anorthosites show more or less evidence of undeformed igneous textures the acidic rocks are invariably strongly foliated with no satisfactory evidence of an igneous origin. Finally, it is recalled that preliminary data on the rare earths indicate a separate evolution for the anorthosite and mangerite of the so-called Morin series (see chapter 1).

Despite its distinguished pedigree (it was first proposed by Bowen in 1917) there appears to be little to recommend this theory apart from the frequency with which anorthosites are conterminous with acidic gneisses[1], a rock-type which, after all, is not noted for its rarity in the Shield. I suggest misplaced emphasis has been laid on the fact that these rocks are pyroxene-bearing, resulting in their being christened with magmatic-slanted names. The present work suggests that the pyroxene phase may be of contact metamorphic origin although, of course, some of these rocks may

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[1] Although commonly called syenites there is actually a wide range in quartz content in these rocks: e.g. Morin area - 7-21% (Philpotts' Table 4), Adirondacks 2-31% (Buddington 1963, Table 6), Nain area - 10-40% (Wheeler 1942, p. 620).

in fact be orthogneisses. Table 4-6 attempts to indicate that such an origin may also apply to most anorthosites: in particular recall the observation of Hargraves (1962, p. 178) who states, "the pyroxene syenite would therefore appear to constitute a distinct facies of the (biotite) granite restricted to the immediate vicinity of the anorthosite massif".

6f. Origin of an Anorthositic Magma

Having indicated my reading of the available evidence is not compatible with the anorthosite originating as an early basic cumulate from a differentiating magma, there remains the possibility of a (gabbroic) anorthosite magma. As suggested above there are two ways of deriving such a magma, either directly by partial melting of the mantle (Buddington 1961, Hargraves 1962), or by appropriate crystal fractionation to produce a magma highly enriched in the components of intermediate plagioclase. In this section the theoretical merits of these theories are discussed on the basis of recent experimental work.

On the basis of their hydrothermal experiments Yoder & Tilley (1962, p. 461) note that a plagioclase-rich magma could be theoretically derived by partial melting of an amphibolite. For amphibolites of diverse compositions plagioclase is the first phase to be completely melted with increasing T. at water pressures above 1-5 Kb. From their figure 27 it is noted that sphene is the next phase to be completely dissolved so that the Ti/Fe ratio of the liquid would increase relative to the original rock. (Note Ti-ores are a characteristic feature of anorthosites.) Further, attention is drawn to the fact that, depending on the amphibolite, the plagioclase could be quite variable in composition but would tend to be more albitic than plagioclase of a basalt of equivalent bulk composition[1]. All these combine to make this an attractive theory since various processes (e.g. filter-pressing) can be invoked to separate liquid from remaining solid phases at an early stage after initiation of melting. In essence this is the process proposed by Buddington (1961) who based his theory on Yoder's demonstration (1955) of the dramatic shift in the eutectic composition in the system Di-An with increasing P_{H_2O}.

However, Yoder & Tilley (1962) pose the question "If so - where are the residual hornblendites?", implying that the unquestionable lack of such bodies of requisite size associated with massif anorthosites argues against such an origin. It should be emphasised, however, that this criticism itself begs the question of the locale of the partial melting; Yoder & Tilley appear to reason that there has been little movement of the magma since separation.

If, as argued by Buddington (1961), partial melting occurred in the mantle the residua would not be expected to be seen. Of course, this in turn raises the question of the status of water in the mantle - an exceedingly moot point, so moot in fact that there seems little profit in considering it here. As Yoder & Tilley (1962) point out, the existence of an amphibolite layer in the mantle as proposed by Wagner (1928) would serve as an appropriate reservoir for water; the possibility of the stability of phlogopite in the mantle is of similar significance. An important concept that can be borne in mind, however, is that no matter how little water is available the first melt to form will be H_2O-saturated

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[1] In amphibolite some plagioclase tends to occur as occult solid solution in the amphibole - see Lacroix (1917).

- therefore the problem of scale arises since as % of water decreases so does the % of rock that can be melted to give a H_2O-saturated magma. In other words, with a small % H_2O a proportionally larger volume of rock must be partially melted to give a similar total volume of magma. This will also affect the composition of the melt unless this first composition is a minimum in the particular system (e.g. as in granites).

Of importance to the problem of anorthosites is the course of crystallisation of such a magma if produced in this manner: could it in fact crystallise as an anorthosite as they actually occur? Theoretically such a magma would initially be H_2O-saturated - but, Kranck (1961), Emslie (1965) and Philpotts (1966) have argued that the anhydrous mineralogy of anorthosites rule out a water-rich magma. Several explanations of this apparent non-sequitur are possible including, as Emslie (1965) suggests, a change in the H_2O content of the magma between generation and emplacement - a mechanism he, without comment, finds distasteful. However, it is not certain that the anhydrous assemblage (i.e. pyroxene vs. amphibole) does indeed signify a very low P_{H_2O} since, as comparison of figs. 27-30 in Yoder & Tilley (1962) demonstrates, the relative stability of pyroxene and amphibole (under $P_{H_2O}=P$ total conditions) is controlled to a large extent by the bulk composition of the system. It would be instructive to repeat the experiments of Yoder & Tilley using a gabbroic anorthosite composition. As a further comment on the state of the magma it will be recalled from chapter 5 that the uralitisation, scapolitisation and the metasomatism were all ascribed to a continuation of igneous processes so that, for the Whitestone body at least, considerable quantities of volatiles must have been generated during crystallisation; it is not unreasonable, therefore, to suggest magma was not in fact completely anhydrous.

As shown in fig. 6-7 a very similar mechanism for generation of an anorthositic magma follows from the work of Clark et al (1962) in the system SiO_2-$CaMgSi_2O_6$-$CaAl_2SiO_6$ at 20Kb and 1 atmosphere. They argue that partial melting at the high P. eutectic will produce a melt which, intruded to lower pressures, will be superheated and will have a composition within the plagioclase field so that large quantities of plagioclase will be the first mineral to crystallise.

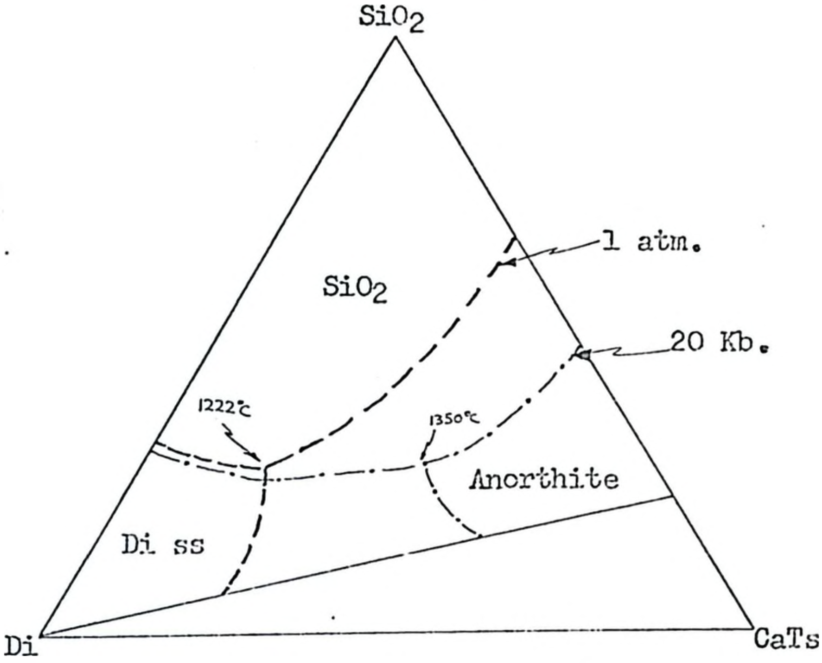

Fig. 6-7 System SiO_2-Di-CaTs at 1 atm. and 20 Kb. (Dry)

It is noted that the above mechanism involves an essentially dry melt in contrast to the previous which produced, at least initially, a H_2O-saturated melt. This point is of fundamental importance in designing experiments bearing on the origin of anorthosites which must ultimately be consistent with field data. As noted above, many contemporary workers interpret the field data to indicate that the magma was very dry, and such a conclusion has governed the choice of experimental conditions of Green (1966) and Lindsley & Emslie (1968,69)[1]. In this thesis I have interpreted the petrographic, chemical and field evidence to indicate that towards the end of crystallisation the magma was very rich in volatiles (mainly H_2O): apparently the P_{H_2O} was much higher than in such dry magmas as the Skaergaard. Such an interpretation casts doubt on the validity of an extremely dry anorthositic magma. Of course the source of the water remains debatable: was it magmatic or was it leached from the surrounding rocks as would seem to be indicated by the oxygen-isotope work of Taylor (1966) for the Adirondack anorthosite? - see chapter 1. In any event, I contend that the data forwarded in previous chapters is consistent with a relatively water-rich magma during the crystallisation.

It is significant to note that most present day work and theories on anorthosite genesis rest ultimately on the profound change in the eutectic composition in the pseudo binary system $CaMgSi_2O_6$-$CaAlSi_2O_8$ (Yoder, 1955) - and it is noted that such a shift is produced both by high, dry pressure and by a much lower water pressure - the latter also lowering the temperatures. See fig. 6-8. Now the principal objection of Bowen (1917) to the existence of an anorthositic magma was the unreasonably high temperatures apparently involved: the effect of water pressure is to alleviate this criticism while increasing dry, total pressure acerbates it.

In the above discussion the An-Di eutectic shift has been utilised in considering derivation of an appropriate magma directly and, indeed, such a mechanism would appear to be theoretically feasible. However, this phenomenon is also relevant to the alternative of deriving such a magma - crystal fractionation. In this type of theory an attempt is made to derive the anorthositic magma from an ancestor of loosely 'basaltic-type', on the premise that such magmas are the most common, occurring in

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[1] The relevance of the work of Yoder & Tilley (1962) and Clark et al (1962) to anorthosite genesis was an intriguing offshoot rather than the purpose of the experiments.

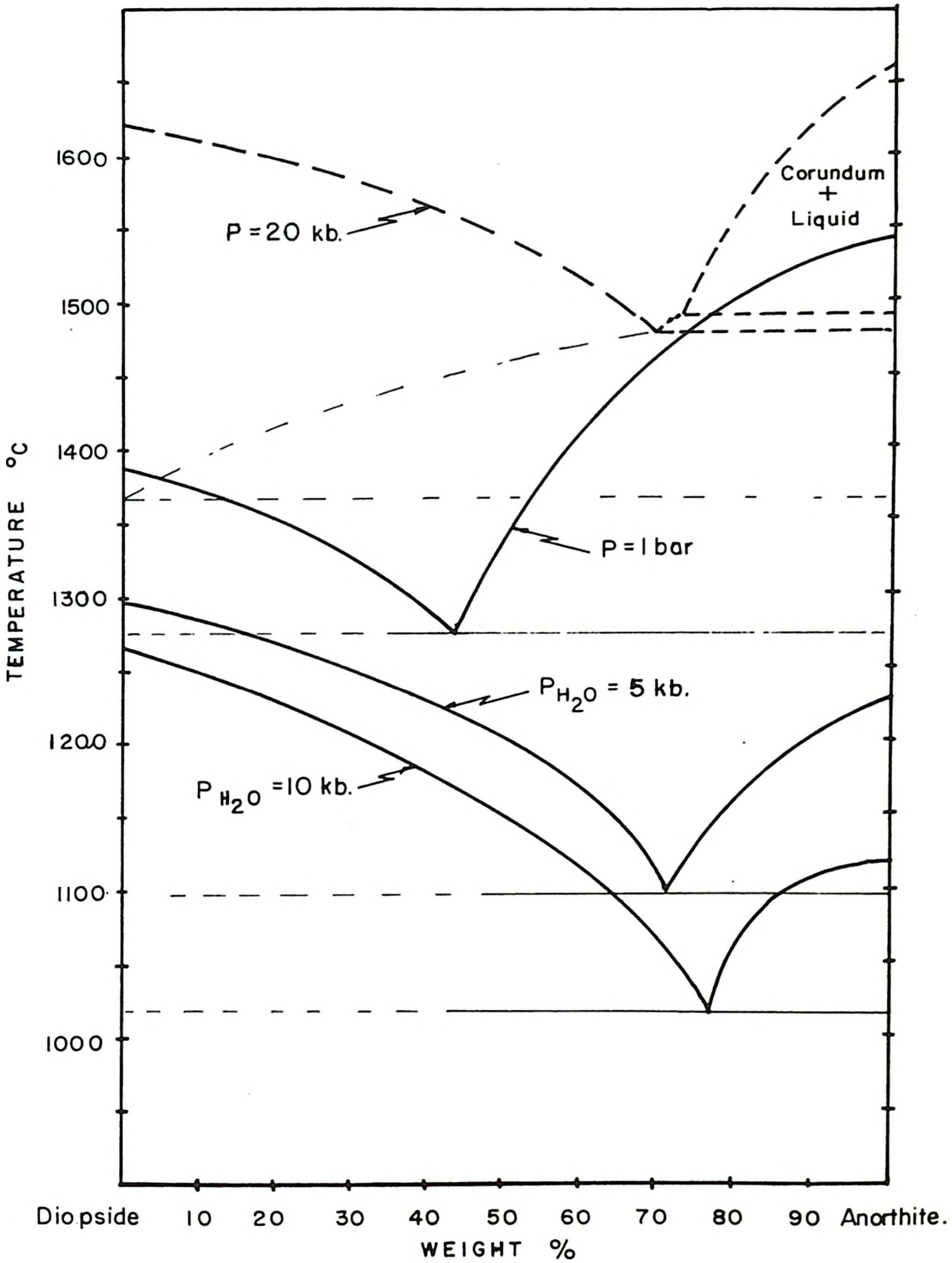

FIG 6-8 Effect of pressure and water vapour pressure on the system DI-AN.

vast quantities in all periods of the earth's history.

To be acceptable such a theory must explain an enrichment in the components of intermediate plagioclase: i.e. it must allow of the following, simultaneous enrichments:-

1) Al(+Ca+Na) relative to Mg(+Fe+Ti)
2) Ti, Fe relative to Mg,
3) Na relative to Ca[1].

Such results could be achieved by fractionating from a basic magma a mixture of diopsidic clinopyroxene and enstatitic orthopyroxene (or fosteritic olivine) probably with minor basic plagioclase. A relevant question is - "Is such a mechanism theoretically reasonable?" Lindsley & Emslie (1968,69) have addressed themselves to this problem. In the system Ab:An:Di at 1 atmosphere normal basaltic compositions plot in the plagioclase field but as noted above, both water and dry total pressure shift this boundary towards the plagioclase sideline. Lindsley & Emslie (1968), working on the basis of a dry magma, show that dry pressures in excess of 15-20 Kb. are necessary to put pyroxene on the liquidus and they note that at such pressures it is unlikely plagioclase is stable in a complex silicate system. On this basis they conclude this system provides an inadequate model for the derivation of an anorthositic magma. However, the following comments are applicable here:-

1) As has been remarked by many authors there are no large, mafic bodies in the general locality of massif anorthosites so that

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[1] Although anorthositic plagioclases are (on the average) not muc richer in Ab than an average basalt or gabbro, these latter rocks contain much larger quantities of Ca-rich cpx.

if this mechanism has been active it occurred at some other level in the crust, i.e. plagioclase need not be stable under the conditions the mafic minerals separated.

2) If, as suggested in this work, anorthositic magmas are more volatile-rich than commonly allowed, then a satisfactory boundary-shift can be achieved by pressures much lower than 20 Kb.

3) It has been noted above that the relative stability of pyroxene and amphibole is a function of magma composition. It must also be appreciated that in Yoder & Tilley's work (1962) H_2O was the only volatile and, while it seems reasonable that $P_{fluid} = P_{total}$ in a magma, the presence of other volatiles (e.g. CO_2, S, Cl + vapour pressure of magma) will lower the P_{H_2O} required to attain the same P_{fluid}.

Possibly of extreme relevance to such a theory is the opx-cpx cumulate rock occurring as a block in the anorthosite (chapter 5); this rock may represent a portion of cumulate material carried up from a greater depth. It is hoped to start detailed petrographic and chemical work (including e.g. rare earths)[1] on this block in an attempt to comment on its genetic relation to the anorthosite. Lacking this data it is perhaps precipitous to favour this interpretation over the theory deriving an anorthositic magma directly by partial melting.

6g. Crystallisation of the Anorthosite

In discussing the crystallisation of anorthosites virtually al

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[1] Age data, if possible, would also be a useful parameter.

workers have appreciated the uncanny chemical homogeneity, within single crystals and over the body, in both plagioclase and pyroxene and, in general, an exotically long crystallisation history has been considered an adequate explanation. However, I am not happy that this feature can be rationalised so simply unless it be assumed that the anorthositic magma had a composition very near a multicomponent eutectic so that the complete magma would crystallise with little differentiation. There is no basis for such a supposition while, on the other hand, there is compelling evidence for solidification by crystal accumulation.

For example, the glomeropoikilitic texture (Plate 5-2) is virtually identical with the heteradcumulate rocks of Askival and Hallival in Rhum, (Brown 1956, see Wager (1960) for definition of textural terms), although somewhat different in mineralogy. Such a texture can be explained (after Wager 1960, p. 78ff) by very slow settling of plagioclase crystals with addition of sufficient plagioclase to each crystal at the same temperature[1], while it lay at the top of the crystal pile to completely eliminate all pore liquid - thus accounting for the pure plagioclase domains. At the same time there was growth (components from the overlying magma) of very rare pyroxene nucleii to form the glomerophenocrysts: because of lack of zoning in pyroxene it is unlikely that this mineral represents trapped liquid. Again, such structures as illustrated in Plate 2-9 are hard to visualise as other than gravity stratified features. Further, many anorthosites (e.g. Morin (Philpotts 1966), Sept Isles (Faessler 1943) and Michikamau (Emslie 1965)) show well laminated plagioclases: this structure has not been recognised in the Whitestone anorthosite perhaps because of

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[1] Therefore no zoning.

the pervasive recrystallisation.

If crystal accumulation is the manner of solidification then the lack of cryptic layering is indeed surprising. The explanation may very well lie in the phenomenon recognised by Wyllie (1963) in which he deduces that the addition of diopside has the effect of drastically steepening the slope of the liquidus and solidus in the plagioclase system, with the result that relatively large temperature drops have only a slight effect on the solidus composition. I also suggest that the effect of the phase boundary shift due to water pressure may enhance this effect since the liquidus, at least, can be shown to steepen.

6h. Oxide Minerals in the Anorthosite

A further, ostensibly anomalous feature of the crystallisation, apparently common to many anorthosites, is the lack of iron enrichment in the pyroxene compared to the iron enrichment of the rocks - see fig. 6-4c. As noted above, various authors have postulated relatively strong oxidising conditions and at first sight this would appear to be a reasonable hypothesis for anorthosites considering the relatively high vapor pressure that has been induced at various points in this thesis[1]. On the other hand, such phenomena as the green feldspar facies, the uralitisation, the metasomatism and the mode of occurrence of oxides in the anorthosite (see e.g. Plate 2-15) all indicate that rather than being present in the magma as potential iron oxides the Fe and Ti have apparently actually fractionated into the vapor phase. Compare, for example, the Kap Edvard Holm

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[1] Making the usual assumption that P_{O_2} is proportioned to P_{H_2O}, however note that vapor pressure is not equivalent to water pressure: as Verhoogen (1962) points out, the presence of volatiles other than water seriously cuts down the P_{O_2}.

complex where the oxides appear as a cumulus phase early in the crystallisation history (Deer & Abbot, 1965).

It has been postulated for the Allard Lake (Hargraves, 1962) and the Morin, Lac St Jean, Roseland etc. (Philpotts, 1967) that during the crystallisation of these anorthosites an immiscible oxide- and volatile-rich magma separated from the anorthositic magma, intruding both the anorthosite and the surrounding rocks. Philpotts (1967) has produced some experimental evidence indicating that an oxide-apatite liquid is immiscible in a dioritic-type magma.

It does not appear from the evidence in the Whitestone area that a thorough-going oxide magma has formed; (although the decision as to what concentration of rock-forming elements a fluid must contain before it deserves the name magma is probably arbitrary). In any case the data from the Whitestone area is significant in indicating the generating mechanism of such a 'magma'.

In his experimental survey on the genesis of anorthosites Green (1966) studied the crystallisation of a synthetic gabbroic anorthosite but, like Emslie and Lindsley, he accepts the conclusion of a dry magma and so carried out his experiments under dry pressures[1]; moreover, probably because of the non-hydrothermal nature of his work he used very high pressures, 9, 18 and 27 Kb. For the 18 Kb runs Green notes that the glass in equilibrium with the crystals increases in R.I. with decreasing temperature but he gives no chemical data. However, it is noted that opaques do not appear as a crystalline phase in the diagram for the gabbroic anorthosite,

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[1] Green in fact studied the crystallisation of a quartz dioritic magma (with anorthosite as residua and 'mangerite' as differentiates) as well as gabbroic anorthosite. Unfortunately he seems to favour the former theory so that more quantitative data is available for the dioritic magma.

contrasting with the dioritic magma in which opaques are shown as a liquidus phase. It would be instructive to repeat Green's experiments on the gabbroic anorthosite at 5 Kb water pressure[1] studying both the chemistry of the crystalline phases, the order of their appearance and the composition of the glass. The present work indicates that the glass should become richer in Fe and Ti with increasing crystallisation.

Summary

The argument set forth in this chapter can be summarised as follows. The existence of the metasomatic aureole indicates that the anorthosite, rather than being a residua from which further crystal fractionations took place, is itself the end product of differentiation which, in turn, suggests a unique 'magma-type' derived either directly from the mantle or by fractional crystallisation of a mother magma. The bulk chemistry of the anorthosite and the pyroxenes are consistent with the existence of such a unique 'magma-type' in being not readily harmonised with previously established types. Important in the genesis of massif anorthosites is the milieu of emplacement which allows of a very slow cooling period resulting in the slow accumulation of crystals. A characteristic of the crystallisation of this 'magma-type' is the development of a Fe-Ti rich fluid phase.

On the other hand, the term 'magma-type' is not overly stressed since chemical and mineralogical differences between various massifs seem to indicate quite a chemical variability. It may well be that the physical processes conducive to both the <u>generation</u> and <u>crystallisation</u>

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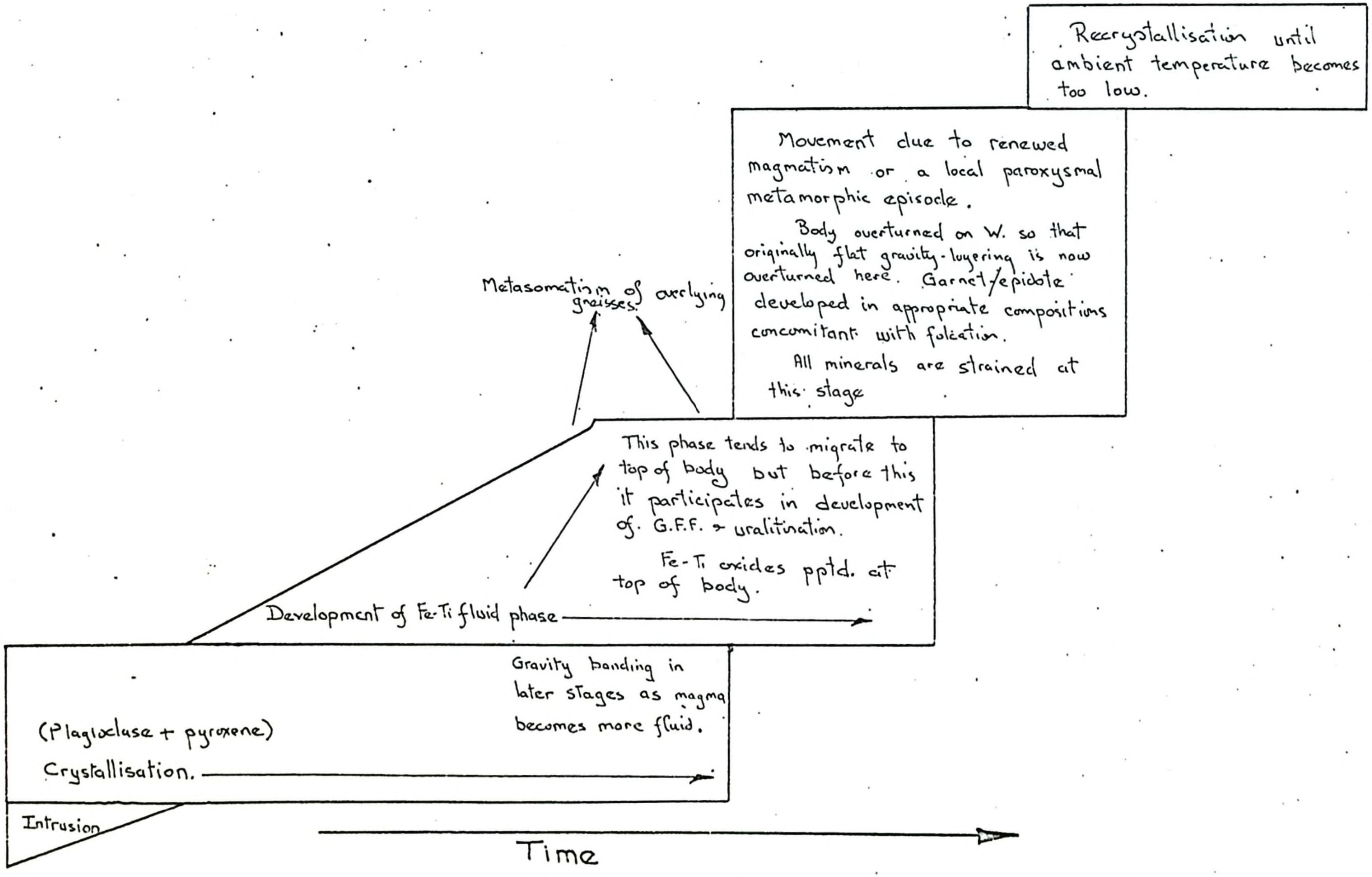
[1] Even 9 Kb seems to be too high to be consistent with the field evidence for the conditions of crystallisation of the anorthosite.



Recrystallisation until ambient temperature becomes too low.

Movement due to renewed magmatism or a local paroxysmal metamorphic episode.

Body overturned on W. so that originally flat gravity-layering is now overturned here. Garnet/epidote developed in appropriate compositions concomitant with foliation.

All minerals are strained at this stage

This phase tends to migrate to top of body but before this it participates in development of. G.F.F. & uralitisation.

Fe-Ti oxides pptd. at top of body.

Gravity banding in later stages as magma becomes more fluid.

Fig 6-9. Diagrammatic Natural History of the Anorthosite of the anorthositic magma are more important than the specific chemistry. In other words, anorthosites are chemically polyphyletic.

Fig. 6-9 illustrates what I visualise as the natural history of the Whitestone anorthosite.

EPILOGUE

In the early 1600s James I of England (VI of Scotland) commissioned Inigo Jones to unravel the mysteries of Stonehenge. His theory that it was built by the Romans has not stood up to further research yet his benediction, for this reason, remains relevant to most scientific endeavour:-

> "Whether, in this adventure, I have wafted by Barque into the desired Ports of Truth, I leave to the judgement of skilful Pilots. I have endeavoured, at least, to give life to the Attempt, trending perhaps to such a degree as either may invite others to undertake the Voyage anew, or prosecute the same in more ample manner, in which I wish them their desired Success and that, with prosperous Gales, they may make a more full and certain Discovery."

Inigo Jones
(Quoted from G.S. Hawkins - "Stonehenge Decoded")

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APPENDIX A

CHEMICAL ANALYSIS

I. X-Ray Fluorescence Spectrometry

I-1. Introduction

X-Ray Fluorescence Spectrometry (X.R.F.) is now accepted as being a rapid, versatile and potentially accurate method of instrumental analysis. Not the least of its appeal is that, once optimum operating conditions have been established, a high degree of precision can be maintained by even inexperienced operators; in fact the whole procedure can be successfully automated for some 30 major and minor elements (Leake. In Press)

In common with other rapid instrumental techniques, the X.R.F. is essentially a comparative tool, its accuracy being directly related to the accuracy of the standards used in erecting calibration curves: and, superimposed on this possibly biased accuracy, there are the deviations, or anomalys, due to the intricate interactions of X-rays and complex matter, such factors generally being subsumed under the term matrix effects, so that the problem of the spectroscopist is to devise procedures which will, with the most efficient blend of accuracy and convenience, ameliorate these matrix effects.

I-2. Sample Preparation

I-2-1. General

For geological problems the most convenient method of sample preparation is to form pellets from the crushed rock powder thereby eliminating the grossest of the inhomogeneities, nevertheless unavoidable matrix effects still remain.

Table (A-1) shows that in quantitative X.R.F. analysis the systematic variations, due to the various matrix effects, are several orders of magnitude greater than random variations, due to electronic noise and fluctuations.

Random Bias	Systematic Bias	
Counting Statistics (f(time) only)	Chemical	Physical
Generator & X-Ray Tube Stability (≃0.1%)	Absorption (Primary & Secondary) (100%)	Particle size (100%)
Equipment errors (< 0.05%)	Enhancement (10%)	Chemical state (5%)

Table (A-1) Possible order of magnitude for main sources of variation in X.R.F. analysis. (After Jenkins, De Vries 1967)

For complex matrices, such as rocks, two types of techniques are available to alleviate these systematic variations. One approach is to use as standards rocks mineralogically and chemically similar to the unknowns. This method, which is, in effect, using an internal standard for both chemical and physical effects, is particularly apt when the samples to be analysed are not expected to have a wide range in composition. The other method is to drown out chemical effects by adding an absorber and to destroy physical effects by fusing to a glass. (Rose et al, 1962)

Preliminary experiments to evaluate the relative efficiency of these methods indicated that, for anorthosites at least,[1] the more time

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[1] Note that for rocks with widely differing matrices the high-absorber-fusion method may be superior.

consuming high-absorber-fusion technique gave only slightly superior results to the modified pure powder method outlined below for the elements Fe, Ti, Ca and K, while results for lighter elements were unsatisfactory by both methods. It should be noted, however, that by using an Ag-target X-ray tube plus an ultra-thin counter window (equipment which was unavailable at time of experiments) it may prove possible to improve the situation with respect to Si, Al, Mg and Na.

I-2-2. Pure Powder Technique

The Spex shatterbox was found to be far superior to more conventional methods for pulverising powder to a fine-grained, relatively homogeneous size. Microscopic examination of powders from the shatterbox indicates that approximately 95% of the sample is less than 15 microns with none greater than 100 microns. (This is to be compared with Table 6-2 p.116 in Jenkins & De Vries, 1967). These authors suggest that particle size less than 50 microns is required for the very light elements Mg, Al and Si, therefore, since this size is achieved and, moreover, all elements analysed are heavier than these, the crushing procedure is held to be adequate.

Considerable difficulty was encountered initially in making pellets which gave a perfectly smooth surface, the dry powder tending to blister, flake off or crack. To counteract this, approximately 2 grms. of rock powder were mixed in an agate mortar with four drops of 2% Moiwol solution for 5 mins. (i.e. until powder is dry). At least two pellets were pressed under a pressure of 30 tons from this mixture. As well as

TABLE (A-2)

	Element	Fe	Ti	Ca	K
	Line	K	K	K	K
	Tube	W	Cr	Cr	Cr
Excitation	Voltage (Kv)	20	40	15	40
	Current (mA)	6	30	8	20
	Collimation	160	160	160	160
	X-Ray Path	Air	Air	Vacuum	Vacuum
	Crystal	LiF	LiF	P.E.T.[1]	P.E.T.[1]
	Attenuation	2^3	2^2	2^1	2^2
	Counter	ScC.[2]	ScC.[2]	Fl.C.[3]	Fl.C.[3]
Analysing	Gas Flow[4]	-	-	1 f.p.s.	1 f.p.s.
	Counter Voltage in Scale Division	240	230	415	432
	Counter Voltage in (volts)	940	910	1,460	1,510
Pulse Height Analysis	Threshold (in Scale Divisions)	110[5]	210[5]	180[5]	95[5]
	Window (in Scale Divisions)	-	220[6]	140[6]	160[6]

[1] P.E.T. : Penta-Erythritol
[2] ScC. : Scintillation Counter
[3] Fl.C. : Flow Counter
[4] Gas used : P. 10 : 90% Argon
10% Methane
[5] 1 Scale Division : 0.005 volts
[6] 1 Scale Division : 0.005 volts

giving a satisfactory, smooth, polished surface to the resultant disc this step is also a useful adjunct in alleviating any sampling errors.

I-3. Operating Conditions

The particular unit used, manufactured by Phillips, consisted of an X-ray generator, a manual, single channel vacuum spectrograph plus detection and counting equipment.

Operating conditions for the unit, given in Table (A-2), were arrived at empirically after a deal of experimentation, their justification resting ultimately in the calibration curves produced. Criteria used in selecting these conditions were:-

1) to obtain favourable peak/background ratio - eliminating need for background correction
2) to annul interference from other element lines
3) to obtain enough sensitivity to derogate electronic noise without overloading counters.

Judicious juggling of the available variables achieved these aims in large part. Pulse height analysis was perhaps the most powerful variable and its application, as given in Table (A-2), successfully reduced the background to virtual insignificance (i.e. peak/background greater than 10/1, insofar as measurements are comparative and not absolute, see Jenkins & De Vries, 1967 p.96). (E.g. for Ti, fig. A-1.) In the case of K pulse height analysis combined with low attenuation successfully alleviated interference from second order FeK$_{\alpha}$ line at 2θ=52.60

I-4. Counting Considerations

Since the random distribution (emission) of X-rays follows a Poisson distribution then,

$$\sigma = \sqrt{\overline{N}} \simeq \sqrt{N} \text{ ——— } (A\text{-}1)$$ (where N is number of quanta measured)

or

$$\varepsilon = \sigma\% = \frac{100}{\sqrt{N}} \text{ ——— } (A\text{-}2)$$

and, therefore, an estimate of the number of counts required for a pre-selected precision can be calculated.

For n replicate determinations the precision is improved by a factor of $\sqrt{n}$,

$$\varepsilon = \frac{100}{\sqrt{N}} \times \frac{1}{\sqrt{n}} \text{ ——— } (A\text{-}3)$$

and in all cases three replicate readings were made on each sample.

$$\varepsilon_{(\text{Total})} = \sqrt{\varepsilon^2_{(\text{counting})} + \varepsilon^2_{(\text{generator})}} \text{ ——— } (A\text{-}4)$$

In general the total random error will be dependent on counting statistics, generator and X-ray tube stability. Equation (A-4)

In the unit used, both Kv and mA are stabilised to better than 0.1%[1], combined stability is better than 0.3%[1].

From equations (A-4) and (A-3) it can be calculated that for a total relative standard deviation of 0.5%, 20,000 counts should be accumulated.

Because no background corrections are necessary, a fixed time count was adopted for its obvious convenience. Counts were taken over a 100 sec. interval which in all cases, except those rocks very low in TiO_2, gave accumulations of greater than 100,000 counts. Probably because of these extra counts and also because stability of generator is better than that specified, precision of counting actually measured was in all cases better than that predicted. (e.g. a series of 10 readings on Ca give a relative standard deviation of 0.16%.)

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[1] Values guaranteed by manufacturer.

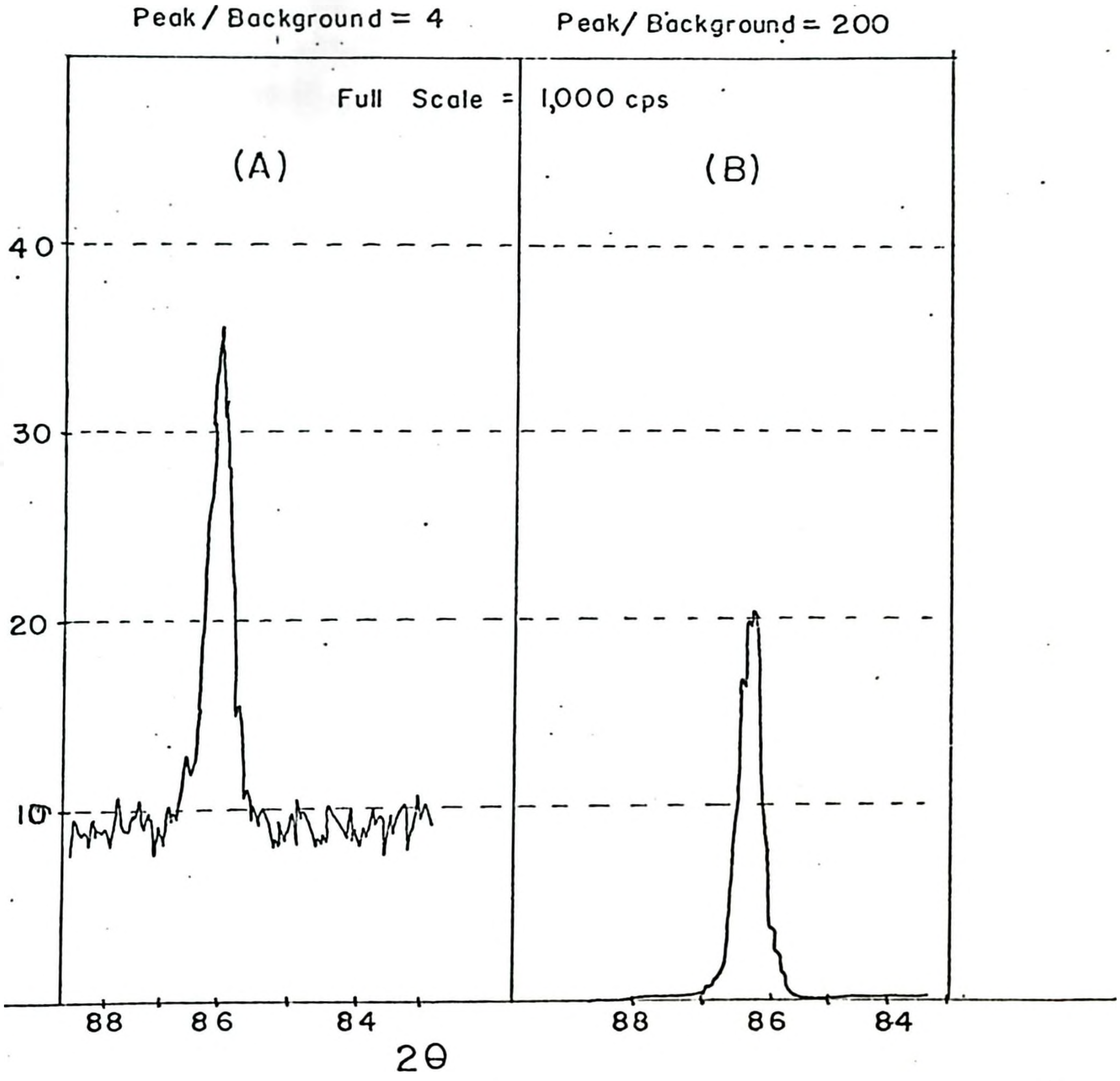

Fig. A-1. Comparative scans over $Ti_{K\alpha}$ without, (A), & with, (B), pulse height analysis.

I-5. Mathematical Corrections

Despite the similarity in matrices of the standards the calibration curves (theoretically straight lines) still show some scatter, especially Fe, in the raw data (lower curve in figs. A-2, A-3, A-4, A-5). This scatter is, in large part, attributable to the phenomena of differential absorption and enhancement. Now mathematical corrections for absorption, which causes the more serious deviations, can be approximated assuming that primary absorption, i.e. absorption by matrix of incident X-ray beam, can be neglected. (It should be noted here that the high-absorber-fusion method circumvents the need for such mathematical corrections and the analyst must decide for each case whether the extra time taken in preparing the samples and the loss in sensitivity justifies the time saved in calculating the absorption correction.)

If the primary absorption can be neglected then the complex general equation for the intensity of excited fluorescent radiation reduces to:-

$$I_{js} = C_j \cdot I_{jp} \cdot \frac{\mu p}{\mu s}$$

or

$$I_{jp} = I_{js} \times \frac{\mu_s}{\mu p . C_j}$$

where:-

I_{js} = intensity for element j in sample

I_{jp} = " " " " " pure j

C_j = concentration of j

μ_p = matrix absorption coefficient for pure element

μ_s = matrix absorption coefficient for sample

i.e. for case of FeK_α:-

Corrected intensity for FeK_α = Measured intensity for FeK_α X ratio

$$\frac{\text{mass absorption coefficient of sample for } FeK_\alpha}{\text{" \quad " \quad " assuming sample is pure Fe, for } FeK}$$

For the standards, the correction factor (i.e. the ratio in the above equation) can be easily calculated since the concentration of the various elements comprising the matrix are known; obviously this cannot be the case for the unknowns. However, in the present case, Si, Al, Na and Mg are known independently from colorometric and atomic absorption determinations and it is suggested that a satisfactory estimate of the wt.% of Fe, Ti, Ca and K can be obtained from the raw data as discussed separately for each element, below.

I-5-1. Fe (Fig. A-2)

Examination of tables of mass absorption coefficient[1] show that, for FeK_α radiation (1.93Å), μ Ca is three times as great as that for other major rock forming elements and this is brought out in untreated data which can be split up into three groups - one each for rocks with 10-12% CaO, 13-15% CaO and 16-18% CaO. Within each of these groups there is surprisingly little scatter and since even the untreated CaO data is sufficient to place rock in one of these catagories (most anorthosites falling in group 10-12%) it is estimated that error in initial estimate of total Fe is less than 0.2%.

The corrected curve is singular in this study in that it is the only one which deviates from statistical linearity[2] while each of the

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[1] Tables used in this study - Appendix 2(c) in Jenkins & De Vries (1967).

[2] Curve fitted by eye since it was felt little would be gained by applying linear regression analysis.

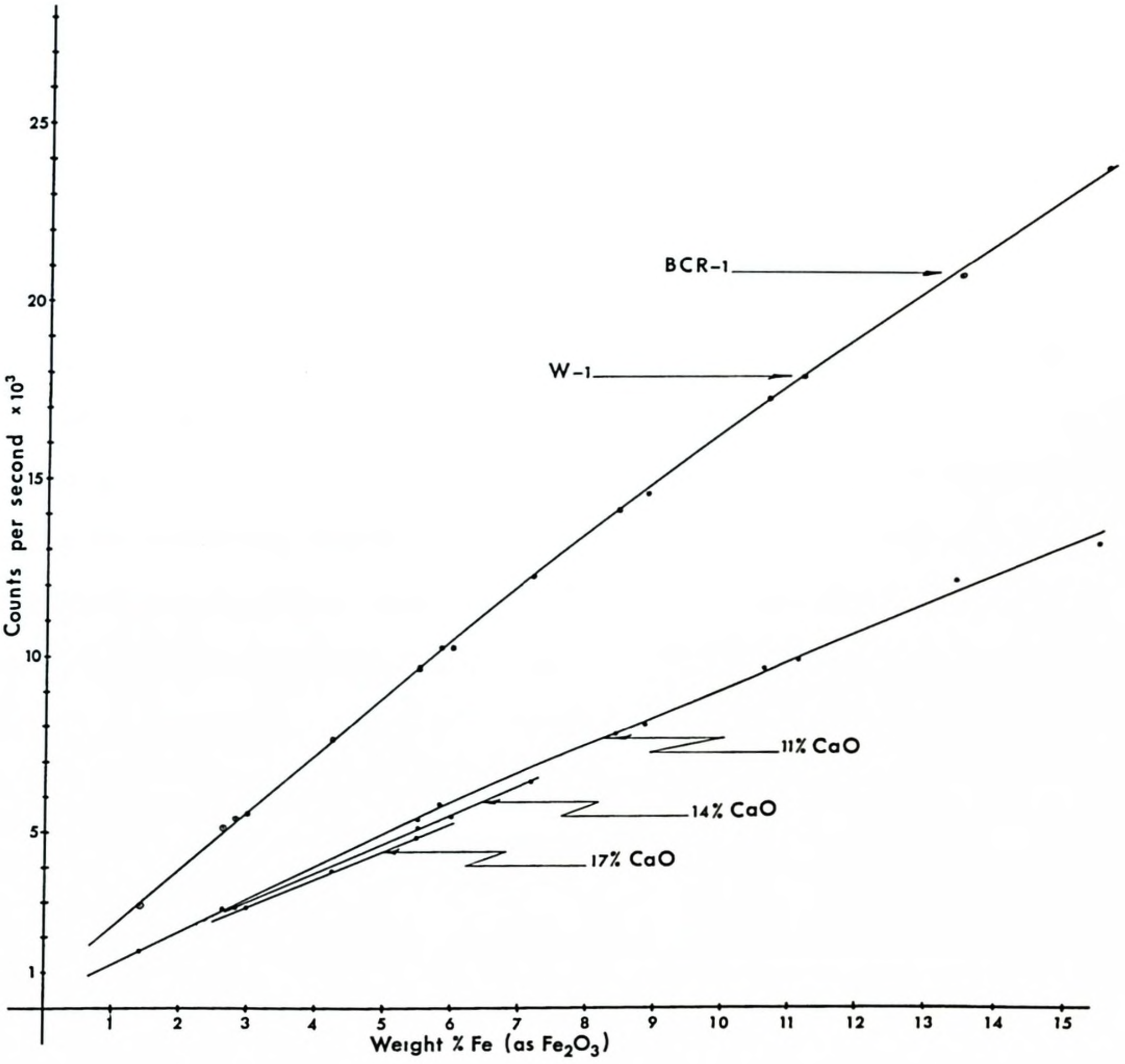

Fig. A-2 Calibration Curve for Fe_2O_3

uncorrected curves is linear, but note that it covers the largest absolute range in wt.%. Assuming no error in the standards (see below) the range of variation about the corrected curve is less than 0.1 wt.%, in fact at the low values of typical anorthosites, i.e. less than 5%, deviation is less than 0.05 wt.%.

I-5-2. Ti (Fig. A-3)

Inspection of lower curve again indicates that an excellent estimate of TiO_2 wt.% can be made from the raw data. Actually, as in the case of K_2O, little is gained by applying absorption correction.

I-5-3. Ca (Fig. A-4)

Again the diagram shows that CaO can be estimated within 0.1 wt.% from the raw data.

In this case, however, it transpires that the absorption correction results in marked improvement only for CaO in range 10-13 wt.% (the range for typical anorthosites - see Table of analyses), at higher values the 'correction' undercorrects, a phenomenon for which there is at present no adequate explanation. Since most anorthosites lie in range 10-13% the fit of corrected curve to standards is seen to be better than 0.05 wt.% while, even if raw data has to be used, fit is good to 0.1 wt.%.

I-5-4. K (Fig. A-5)

Only in the case of K_2O, of the elements studied, did the phenomenon of enhancement seem to be important. Enhancing occurs when matrix element A absorbs characteristic radiation of element B photo-electrically (i.e. opposed to pure scattering) thereby producing extra emission quanta characteristic of A, such photo electric absorption reaching a maximum on the high energy side of the A ^{K}absorption edge. Theoretical corrections

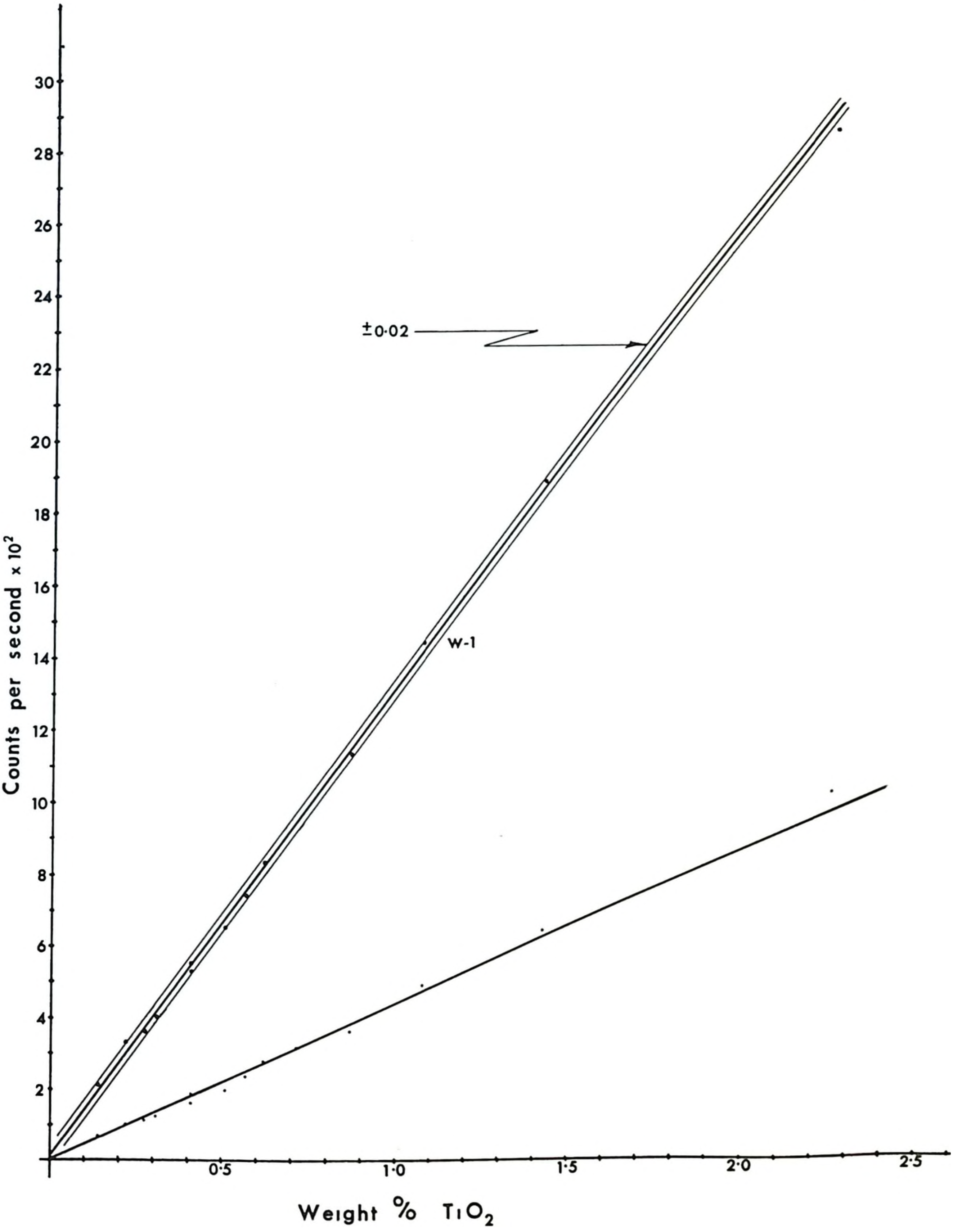

Fig. A-3 Calibration Curve for TiO_2

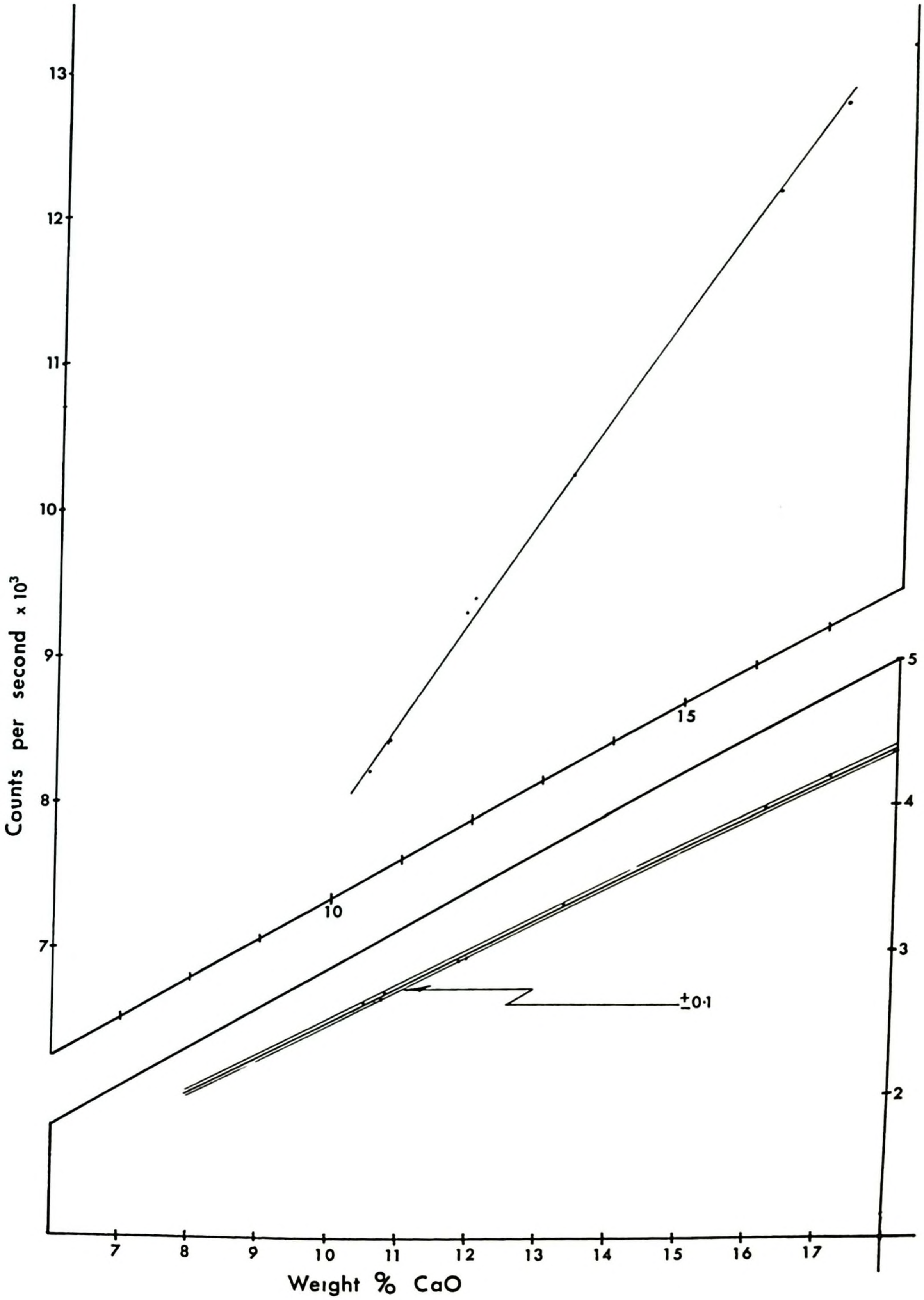

Fig. A-4 Calibration Curve for CaO

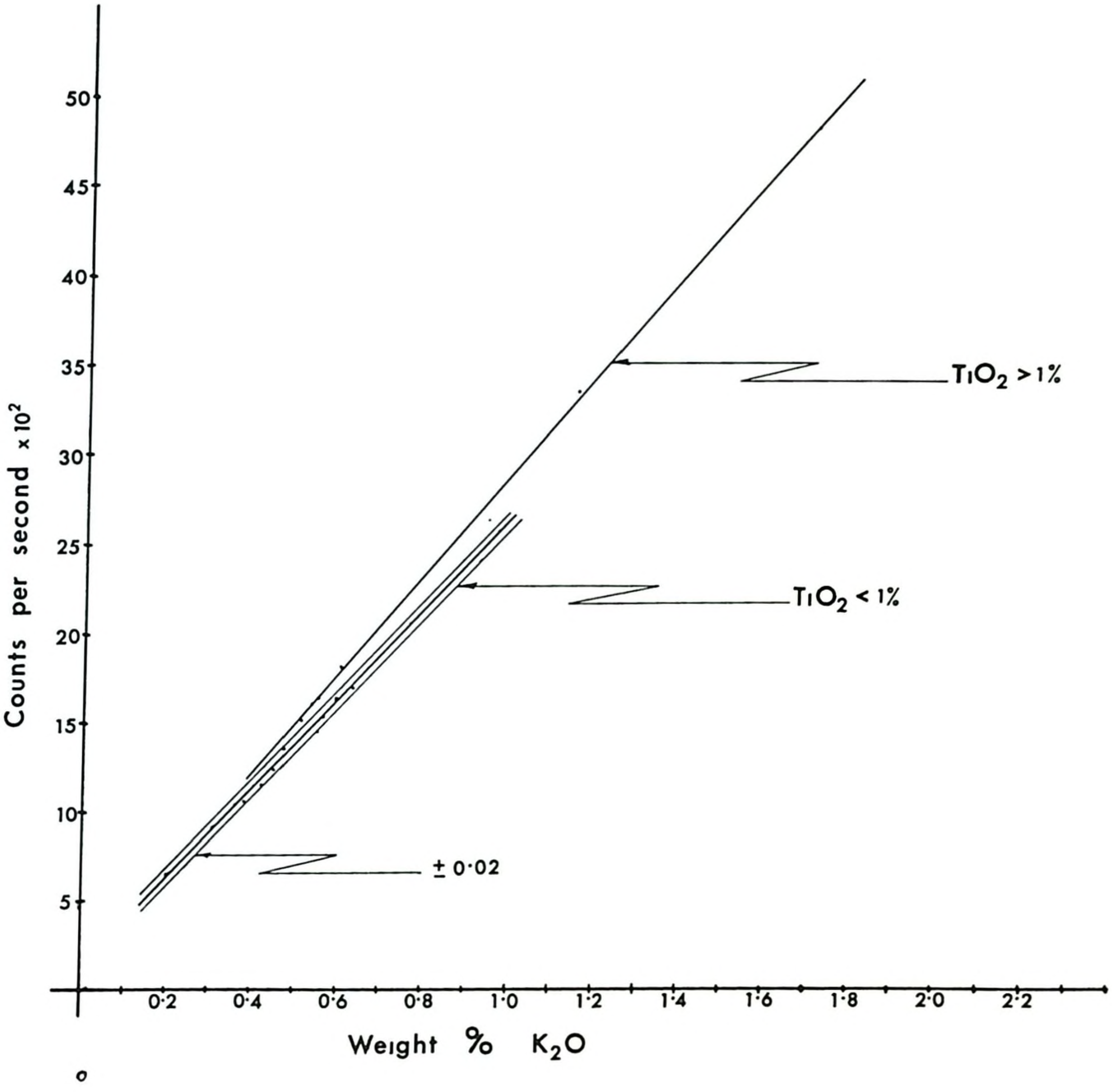

Fig. A-5 Calibration Curve for K_2O

cannot be made for enhancement although the high-absorber-fusion technique is claimed to annul the effect.

It was empirically decided from the plotted points that Ti gave rise to the enhancement and it can be shown that the relative dispositions of the characteristic radiation and absorption edges are favourable to such an interpretation; however, in the complex matrix of a whole rock it is not possible to know why Ca, which has even more favourable K , does not seem to be effective in enhancing K. Moreover, it is not apparent why 1% TiO_2 is crucial figure; however, overlap of the two curves in region 0.5-0.63% K_2O plus the relatively small scatter about the two given curves is felt to be strong presumptive evidence that the interpretation is valid. Table (A-3) indicates spread of TiO_2 values within each group.

Table (A-3)

lower curve	TiO_2%	.51		0.31	0.22	0.62	0.14	0.41		1.08		
	K_2O%	0.20		0.42	0.47	0.55	0.56	0.59		0.63		
upper curve	TiO_2%				2.53	1.33	1.47	1.43		1.89		2.25
	K_2O%				0.51	0.54	0.55	0.60		1.15		1.69

I-6. Standards, Accuracy and Precision

Basic to the procedure outlined above is that all of the rocks being analysed, including the calibrating standards, have a closely similar matrix. Since there exists no recognised standards for anorthositic rocks this necessitated the analysis of seven rocks, chosen to give as wide a spread as possible within the anorthositic field. These rocks were analysed in the Chemical Analysis Laboratory of McMaster University by Mr.

John Muysson. Where necessary to give more adequate spread, or to elaborate on seeming anomalies, extra standards were manufactured by mixing these original standards in various proportions. The recognised U.S.G.S. standards, W-1 and BCR-1, were used where the matrix effect did not appear to be important; e.g. in Fe, Ti and K.

Obviously, the accuracy of the method is dependent on the accuracy of these standards but, unfortunately, logistical considerations precluded isolation of this elusive quintessence. However, considering both the summations of the standards and the reputation of Mr. Muysson, it is believed that assuming the standards to be 100% accurate introduces no serious inexactitude.

Moreover, since theoretically the relation between counts per second and weight percent is linear, scatter about linearity is indicative of internal accuracy[1]. In all cases at least 10 points are used to define the lines and the range of deviation of these points is taken as a satisfactory estimate of this internal accuracy. Table (A-4) summarises internal accuracy for the four elements.

Table (A-4)

Internal Accuracy

	Absolute	Relative (Average)
Fe	0.1 wt.%	2%
Ti	0.02 wt.%	5%
Ca	0.05 wt.%	0.5%
K	0.02 wt.%	4%

---

[1] To avoid confusion I here define internal accuracy as the level of significance of a particular conversion from counts per second to weight percent,

Precision is a much easier target to circumscribe and various experiments were conducted to evaluate it. Starting from the whole rock powder precision can be divided into that due to precision of machine and that due to precision of pellet manufacture.

The machine itself is very precise, as discussed in section I-4, and Table (A-5) gives a series of readings taken on the same sample at 5 min. intervals, each value being the mean of three readings, i.e. normal procedure during analysis.

Table (A-5)

FeK_{α}

1	2794 c/s	7	2794 c/s
2	2792 c/s	8	2794 c/s
3	2800 c/s	9	2794 c/s
4	2795 c/s	10	2796 c/s
5	2799 c/s	11	2787 c/s
6	2798 c/s	12	2792 c/s

The significance of this precision is dramatised by realising that in Fig. (A-6) the plotted point plus enclosing circle encompasses 100 c/s on the vertical scale while the total range in the above table is 13 c/s.

For the other elements analysed machine precision is equally satisfactory.[1]

Table (A-6) indicates that precision of pellet manufacture is also

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[1] Several weeks work was invalidated when it was discovered that 'sample-to-X-ray tube' distance was not equal in all positions of sample changer. A misalignment of 1/500" resulted in sample in position 4 giving a count rate 2% smaller than same sample in position 1. It is suggested that this be checked periodically by running the same sample in the 4 positions and adjusting if necessary.

excellent although somewhat poorer than machine precision. From each of several representative rock powders four aliquots were taken separately through the various simple preparation stages and the results are summarised in Table (A-6).

Table (A-6)

Results for FeK

Rock No.	Aliquot 1	Aliquot 2	Aliquot 3	Aliquot 4	Range
L3-146	2514c/s	2503c/s	2529c/s	2511c/s(1)	25c/s
LO-T-32	1084	1089(2)	1089(3)	-	5c/s
L3-120	1831	1840	1832	1833	10c/s

Notes:-

(1) Contains double amount of Moiwol binder.

(2) " " " " " "

(3) Contains no binder.

Results for other elements are equally good.

Precision for both machine and pellet manufacture are well within the range of internal accuracy summarised in Table (A-5).

In conclusion, it is held that the results obtained from the X.R.F. procedure outlined above easily stand up to the strain of deductions put on them in the body of the thesis.

II. Rapid Chemical Analysis

As noted above the lighter elements Si, Al, Mg and K could not be determined satisfactorily by X-Ray spectrometry: they were analysed as the appropriate oxides by conventional 'rapid silicate analysis' techniques by the author under the tutelage of Mr. John Muysson.

SiO_2 and Al_2O_3 were analysed colorimetrically using a NaOH fusion.

K_2O and MgO were analysed by atomic absorption using a HF and perchloric acid digestion.

Table A-8 lists the 29 whole rock analyses carried out using the combination of X.R.F. and rapid methods. Since minor elements such as MnO were not determined and volatiles were analysed in only a few specimens all totals are low by an appropriate amount.

Table A-7 lists the 7 complete whole rock analyses determined by Mr. John Muysson which were used as standards for the X.R.F. Molecular norms are given for both table A-7 and 8.

TABLE A-7

Analyses of Rocks used as Standards

Lab No Field No	90 L0-67	106 L1-126	107 L1-127	105 L1-303	140 L1-354	142 L1-359	336 L1-189
SiO_2	51.12	48.08	48.62	52.29	50.90	52.57	53.15
TiO_2	1.43	0.31	0.51	0.14	0.41	0.22	0.62
Al_2O_3	21.10	26.60	19.50	28.21	22.04	25.85	22.74
Fe_2O_3	1.72	0.89	1.52	0.67	1.34	0.75	1.97
FeO	6.40	1.90	3.55	0.68	4.02	1.70	3.18
MnO	0.12	0.04	0.08	0.02	0.10	0.04	0.08
MgO	2.57	2.39	5.22	0.82	3.97	2.03	2.48
CaO	10.50	16.19	17.96	11.97	10.80	11.86	10.76
Na_2O	3.30	2.15	1.79	3.91	4.07	3.89	3.36
K_2O	0.60	0.42	0.20	0.56	0.59	0.47	0.55
P_2O_5	0.11	0.02	0.03	0.01	0.04	0.04	0.07
H_2O^+	0.49	0.42	0.46	0.47	1.07	0.44	0.59
CO_2	0.56	0.35	0.48	0.21	0.50	0.13	0.52
S	0.04	0.02	0.02	0.01	0.02	0.02	0.04
Cl	0.01	0.01	0.01	0.01	0.01	0.02	0.02
SrO	0.08	0.11	0.10	0.08	0.07	0.11	0.07
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	100.15	99.90	100.06	100.06	99.95	100.14	100.20
Less	0.02	0.01	0.01	0.01	0.01	0.01	0.02
Total	100.13	99.89	100.05	100.05	99.94	100.13	100.18
				Molecular Norm			
Qtz	2.03	0.00	*	0.67	*	0.27	4.72
Or	3.60	2.49	1.19	3.27	3.50	2.75	3.28
Ab	30.08	17.09	13.65	34.69	34.47	34.55	30.40
An	41.63	61.92	45.02	57.11	40.20	51.15	45.71
Di	4.30	11.46	28.26	1.08	7.31	4.09	4.33
Hd	4.14	3.39	7.55	0.14	3.26	1.36	1.78
En	5.06	0.00	*	1.68	*	3.50	4.74
Fs	4.87	*	*	0.22	*	1.17	1.95
Fo	*	0.67	0.32	*	5.49	*	*
Fa	*	0.20	0.08	*	2.44	*	*
Mt	1.83	0.93	1.62	0.69	1.40	0.78	2.08
Ilm	2.02	0.43	0.72	0.19	0.57	0.30	0.87
Hem	*	*	*	*	*	*	*
Ap	0.23	0.04	0.06	0.02	0.08	0.08	0.15
Ne	*	1.37	1.55	*	1.27	*	*

TABLE A-8

Anorthosite Analyses (No Volatiles)

Lab No Field No	2 L3-25	13 L3-13	17 L3-44	20 L3-146	24 L3-76	30 L3-71	79 L2-82
SiO_2	51.73	53.81	54.00	51.68	48.87	52.19	51.42
TiO_2	1.51	0.92	0.72	1.12	1.73	0.25	0.37
Al_2O_3	20.53	22.46	21.99	22.71	21.11	27.35	22.19
Fe_2O_3	2.86	1.28	1.10	1.50	3.24	0.61	1.06
FeO	6.46	4.70	3.81	5.14	7.45	1.46	2.80
MgO	1.99	1.99	2.07	1.56	3.09	1.00	2.45
CaO	9.76	9.69	11.03	10.37	10.06	11.55	12.32
Na_2O	3.21	4.03	3.60	3.88	3.07	3.80	3.90
K_2O	0.92	0.56	0.81	0.52	0.38	0.44	0.69
H_2O	nd	0.51	nd	0.48	nd	nd	nd
Total	98.97	99.95	99.13	98.96	99.00	98.65	99.57
Molecular Norm							
Qtz	4.29	2.92	3.60	1.41	1.18	1.46	*
Or	5.57	3.32	4.82	3.12	2.30	2.60	4.15
Ab	29.51	36.26	32.49	35.37	28.20	34.08	33.70
An	39.83	41.64	41.68	43.69	43.69	56.22	41.66
Di	3.76	2.71	6.19	3.05	3.27	0.53	11.23
Hd	4.05	2.52	4.48	3.80	2.63	0.29	5.12
En	3.75	4.15	2.65	2.85	7.09	2.49	*
Fs	4.03	3.86	1.92	3.54	5.72	1.34	*
Fo	*	*	*	*	*	*	0.94
Fa	*	*	*	*	*	*	0.43
Mt	3.06	1.34	1.16	1.59	3.47	0.64	1.13
Ilm	2.15	1.28	1.01	1.58	2.47	0.35	0.52
Ne	*	*	*	*	*	*	1.12

TABLE A-8 (Continued)

Lab No Field No	134 LOT-32	144 L1-369	168 L2-99	181 L1-374	206 L1-111	213 L2-154	214 L2-155
SiO_2	52.51	52.16	52.04	53.92	49.74	52.52	51.17
TiO_2	0.26	0.14	0.40	0.08	1.03	0.12	0.43
Al_2O_3	27.11	27.86	23.83	29.10	24.06	29.07	23.97
Fe_2O_3	0.66	0.64	1.17	0.27	1.50	0.46	1.42
FeO	1.81	0.92	2.16	0.27	5.13	0.40	2.21
MgO	1.37	1.06	2.14	0.27	1.55	0.35	2.84
CaO	11.57	12.03	13.44	12.34	11.30	11.86	13.32
Na_2O	3.92	4.06	3.83	4.24	3.81	4.07	3.30
K_2O	0.45	0.61	0.57	0.37	0.36	0.43	0.44
H_2O	nd	nd	nd	nd	nd	nd	nd
Total	99.66	99.48	99.58	100.86	98.48	99.28	99.10
Molecular Norm							
Qtz	*	*	*	1.22	*	1.09	0.14
Or	2.63	3.56	3.34	2.13	2.16	2.51	2.60
Ab	34.77	35.55	31.71	37.02	34.66	36.12	29.58
An	54.40	55.24	45.78	57.66	48.13	58.17	49.23
Di	0.98	2.29	11.72	1.30	3.05	*	10.87
Hd	0.87	0.62	3.92	0.21	3.90	*	2.54
En	2.94	*	*	0.07	0.46	0.96	2.39
Fs	2.61	*	*	0.01	0.59	0.13	0.56
Fo	0.23	1.30	*	*	1.76	*	*
Fa	0.20	0.35	*	*	2.25	*	*
Mt	*	0.66	1.21	0.28	1.59	0.48	1.48
Il	0.36	0.19	0.55	0.11	1.45	0.17	0.60
Ne	*	0.24	1.44	*	*	* .37C	*

TABLE A-8 (Continued)

Lab No Field No	218 L2-161	222 L2-143	241 L3-133	248 L2-165	250 L2-166	260 L2-182	261 L1-164
SiO_2	52.57	50.20	52.06	51.17	50.55	51.85	53.12
TiO_2	0.16	1.95	0.42	0.98	0.49	0.22	0.11
Al_2O_3	27.82	21.37	25.91	22.99	24.75	26.90	28.59
Fe_2O_3	0.49	1.22	1.03	1.65	0.83	0.71	0.27
FeO	0.88	5.52	1.96	4.62	3.50	2.03	0.48
MgO	0.78	2.41	1.21	2.64	2.12	2.08	0.53
CaO	12.84	10.82	12.35	11.26	12.07	11.80	12.02
Na_2O	4.05	3.58	3.98	3.37	3.81	3.74	4.39
K_2O	0.39	0.46	0.50	0.53	0.55	0.24	0.42
H_2O	nd	nd	0.39	nd	nd	nd	nd
Total	99.98	97.53	99.81	99.21	98.67	99.57	99.93
Molecular Norm							
Qtz	*	0.87	*	1.02	*	0.09	*
Or	2.27	2.80	2.94	3.15	3.26	1.40	2.43
Ab	35.68	33.02	35.49	30.44	31.73	33.18	38.59
An	55.62	42.01	51.02	46.33	48.89	55.26	55.91
Di	4.08	6.01	5.18	4.83	5.18	1.48	1.58
Hd	1.52	4.50	2.69	3.07	3.69	0.60	0.43
En	*	3.83	0.56	4.92	*	4.94	*
Fs	*	2.87	0.29	3.13	*	2.01	*
Fo	0.06	*	0.13	*	2.45	*	0.48
Fa	0.02	*	0.07	*	1.74	*	0.13
Mt	0.50	1.31	1.07	1.74	0.87	0.73	0.28
Il	0.22	2.79	0.58	1.37	0.68	0.30	0.15
Ne	0.03	*	*	*	1.52	*	0.01

TABLE A-8 (Continued)

Lab No Field No	274 L2-183	283 L2-175	297 L1-162	344 L1-222	352 L3-119	357 L3-120	372 L2-5	376 L2-12
SiO_2	52.35	52.11	51.99	53.11	51.98	52.93	52.67	51.44
TiO_2	0.17	0.36	0.23	1.54	0.18	0.64	0.41	0.68
Al_2O_3	26.63	25.03	26.63	19.51	25.82	24.02	26.09	25.66
Fe_2O_3	0.67	1.00	0.66	2.25	0.82	1.17	1.14	1.32
FeO	1.64	2.00	1.39	5.55	1.38	3.09	2.00	2.68
MgO	1.94	2.05	1.87	2.02	2.07	1.66	1.53	1.06
CaO	12.06	12.82	13.21	9.87	12.27	10.22	11.15	10.92
Na_2O	3.69	3.89	3.81	3.60	3.71	3.74	3.65	3.77
K_2O	0.28	0.49	0.30	0.66	0.47	0.92	0.80	0.74
H_2O	nd	nd	nd	nd	nd	nd	nd	nd
Total	99.43	99.75	100.09	98.73	98.70	98.39	99.44	98.27
Molecular Norm								
Qtz	0.98	*	*	5.56	0.31	2.45	1.74	1.09
Or	1.64	2.86	1.74	4.01	2.77	5.49	4.71	4.42
Ab	32.80	33.66	33.10	33.23	33.19	33.87	32.58	34.17
An	54.73	48.82	53.72	36.13	52.24	46.45	52.16	51.40
Di	2.69	8.41	6.74	6.07	5.48	2.25	1.62	1.48
Hd	0.92	2.82	1.79	5.32	1.26	1.51	0.67	1.16
En	3.96	*	*	2.70	2.95	3.50	3.39	2.21
Fs	1.36	*	*	2.36	0.68	2.35	1.39	1.73
Fo	*	1.04	1.28	*	*	*	*	*
Fa	*	0.35	0.34	*	*	*	*	*
Mt	0.69	1.03	0.68	2.42	0.85	1.23	1.19	1.39
Il	0.23	0.50	0.32	2.21	0.25	0.90	0.57	0.96
Ne	*	0.51	0.30	*	*	*	*	*

APPENDIX B

MODAL ANALYSES

The modes of 360 anorthosite specimens and 105 country rocks were estimated using thin sections (approx. 1,000 sq. mm) and a Zeiss microscope mechanical stage. These specimens are located on Maps 2a and 2b and the modes are collected in Tables B-1, -2, -3 and -4.

For the anorthosite rocks 1,000 points were counted on each thin section except where plagioclase constituted >95%, in which case the mode was visually estimated. Increasing the point count to 3 per sq. mm does not significantly alter the estimate of the mode of the thin section. E.g.

Specimen 54

	Plag.	Scap.	Pyx.	Amph.	Garnet	Epidote	Opaque	Qtz.
3,000 pts.	86.2	2.3	2.5	5.6	1.7	0.6	0.5	0.6
1,000 pts.	86.0	2.4	2.6	5.9	1.5	0.7	0.6	0.3

Thus the given modes are supposed to be adequate estimates of the thin sections; the significance of the thin section as an estimate of the rock outcrop from which it comes is less certain. However, several points combine to blunt the acuteness of this problem.

1) The preparation of the modal diagrams in Chapter 5 are based on at least 4 specimens from the same locale.
2) The ratio of two minerals (e.g. plag/scap) is much less sensitive to the limitation.

3) The timbre of the conclusions drawn in the body of the text (mainly Chapter 5) are not critically dependent on absolute values; relative magnitudes are much more significant.

The parageneses listed in Tables B-2, -3 and -4 are of more importance than the actual numerical modes given; the latter are listed to indicate the enrichment in garnet and oxides of the metasomatised gneisses (Table B-2) compared to the others.

Symbolism of Table B-1

Principal Minerals

An = Anorthite content of plagioclase estimated by Michel-Levy method.

Plag = Plagioclase; Scap = Scapolite; Pyx = Clinopyroxene; Amph = Amphibole; Gt = Garnet; Ep = Epidote; Opq = Opaques; Sph = Sphene.

Others

C = Carbonate; Q = Quartz; S = Serpentine; O = Orthopyroxene; Z = Apatite.

For the above the symbol is given as superscript to the modal value.

90*, 7*, 3* etc. indicates mode was visually estimated.

- indicates absent.

Tr = Trace amount i.e. $<0.25\%$

Values rounded off to nearest whole number excepting those less than 1%.

Symbolism of Tables B-2, -3 and -4

As above except asterisk (*) indicates presence of this mineral in specimens for which there is no mode given.

TABLE B-1

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
1	L0-T-9	50	57	1	1	33	0.5	–	0.5	–	4^{Q},2.5^{C}
2	L3-25		57	10	7	17	7	1	1	Tr.	
3	L3-27	52	67	8	Tr.	7	11	–	7	Tr.	
4	L3-28										
5	L3-45		69	3	7	18	2	–	1	Tr.	1^{C},Tr.^{Z}
6	L3-15										
7	L3-12	51	60.5	18	0.5	10	10	–	0.5	0.5	
8	L3-41	52	68	4	–	19	3	4	1	Tr.	1^{C}
9	L3-10		67	8	–	15	2.5	6	1	0.5	
10	L3-9	–	56	1	–	32	7	Tr	0.5	3	Tr^{Z},Tr^{Q}
11	L3-8	48	53	18	Tr	24	Tr	1	1.5	1.5	Tr^{Z}
12	L3-7										
13	L3-13		72	1	5	14	7	–	1	0.5	Tr.^{C}
14	L3-11		64	12	3	14	5	Tr.	1	Tr.	1^{Q}
15	L0-39	48	40	10	23	11	12	–	1	0.5	1^{C},3^{Q}
16	L3-42										
17	L3-44		79	9	4	4	4	–	0.5	Tr.	Tr.^{C}
18	L3-45		69	3	7	18	2	–	1	Tr.	1^{C},Tr.^{Z}
19	L1-272	52	43	29	–	11	12	1	2	–	2^{Q}
20	L3-146		43	29	–	19	8	–	1	–	Tr.^{Q},Tr.^{Z}
21	L3-150	55	63	19	0.5	15	2	–	1	–	Tr.^{Q},Tr.^{C}
22	L3-151		65	9	3	22	–	–	Tr.	–	
23	L3-152										
24	L3-76		48	12	6	8	21	–	5		
25	L3-75										
26	L3-74		69	14	2	10	5	–	Tr.	–	Tr.^{C}
27	L3-78	56	44	0.5	14	17	11	–	0.5	–	11O,1Q,Tr^{Z}
28	L3-73	59	73	–	3	2	16	–	6		
29	L3-72	55	89	2	6	2	1	–	Tr.		
30	L3-71	58	59	18	–	21	0.5	0.5	Tr.	–	0.5^{C}
31	L3-70	55	86	6	2	6	1	–	–	–	1^{Q}
32	L3-67	58	64	8	17	15	4	–	–	–	1^{C}
33	L3-66	60	69	7	6	12	1	4	1	Tr.	
34	L1-277	55	74	4	11	6	3	–	Tr.	–	2^{C},S
35	L3-63		65	8	1	7	9	2	8		
36	L3-64	60									
37	L1-296										
38	L3-128		66	19	–	8	6	Tr.	1		
39	L3-130		58	11	5	10	10	–	1	–	4^{S}
40	L1-285	58	78	1	6	13	1	Tr.	0.5	Tr.	
41	L3-131	61	90*	*	8*	*	Tr.	–	Tr.		
42	L1-286	56	71	Tr.	24	3	1	Tr.	1.5	0.5	Tr.^{Q}
43	L1-295	56	80	9	4	6	0.5	1	Tr.	–	0.5^{Q}

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
44	L1-316	58	86	4	4	3	Tr	-	0.5	-	2^{C}
45	L1-317	56	95*		5*	*			*		
46	L1-311	58	52	24	14	10	Tr	-	Tr		
47	L1-310	61	57	10	23	3	1	-	Tr	-	4.5^{S},1^{Q}
48	L1-309	57	84	2	8	2	1	-	Tr	-	3^{S}
49	L1-308	61	72	2	21	4	-	-	Tr	-	1^{C}
50	L1-307	55	95*	-	5*	*	-	-	*		
51	L1-306	60	83	-	-	-	Tr	-	Tr	-	12^{S},3^{C}
52	L1-291	62	71	2	23	1	-	-	-	-	
53	L1-293	55	93	5	-	2	-	-	Tr	-	Tr^{Z}
54	L1-294	55	86	2	2.5	6	1.5	-	0.5	-	0.5^{Z},0.5^{Q}
55	L1-289	59	76	5	17	2	-	-	-	Tr	
56	L1-290	56	53	13	25	7	Tr	-	0.5	-	1^{C}
57	L1-288	55	73	11	1	13	Tr	2	-	Tr	
58	L1-247	58	68	-	16	7	1	-	0.5	-	8^{O}
59	L1-246										
60	L1-248		46	28	1	16	7	-	1	Tr	1^{Z}
61	L3-103										
62	L1-245	60	75	Tr	-	24	-	-	-	-	1^{Q}
63	L3-101		80	6	2	3	7	-	1	Tr	1^{Z}
64	L1-287	59	86	1	7	0.5	5	-	0.5		
65	L1-292	64	90*	3*	3*	0.5	0.5*	-	3*		
66	L1-297	66	50	20	18	12	Tr	-	Tr		
67	L1-315	59	95*	-	5*	*	*	*	*		
68	L1-314	59	78	7	7	8	-	Tr	Tr	Tr	
69	L1-313	58	82	4	Tr	7	5	2	Tr	Tr	Tr^{Q}
70	L2-70										
71	L2-71		67	7	-	20	5	-	Tr	-	1^{Z}
72	L2-63										
73	L2-64										
74	L2-65	44	56	8	-	26	6	-	1	2	1^{C}
75	L2-80	58	49	29	0.5	18	5	1.5	Tr	1	
76	L2-66	55	59	24	-	9	2	5	Tr	1	
77	L2-67	45	63	27	-	9	Tr	1	Tr	Tr	
78	L2-81	53	81	7	4	5	1	Tr	1	Tr	
79	L2-82	56	50	29	6	14	-	-	-	1	
80	L2-79	58	93*	1*	1*	5*	-	-	-	-	1^{Q}
81	L2-75	59	52	15	2	10	7	10	1	1	
82	L2-74	55	36	23	29	11	-	-	-	1	
83	L2-76	58	90*	3*	7*	*					
84	L2-78	58	90*	1*	4*	5*	-	-	*		
85	L2-77	58	95*	1*	3*	1*	-	-	-	-	
86	L1-298	61	95*	1*	-	1*	*	-	-	-	2^{S}
87	L1-128	64	93	2	5	Tr	-	-	Tr	Tr	
88	L1-129	55	95*	1*	3*	1*	-	-	Tr	-	
89	L1-130	62	64	6	3	17	1	7	1	Tr	1^{Q}
90	L0-67	50	77	4	4	1	9	-	4	Tr	1^{C}

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
91	L3-92										
92	L1-236	50	51	8	4	5	21	-	6	2	2^Q
93	L1-121										
94	L1-123	62	70	2	8	16	4	-	Tr	-	1^Q
95	L1-124		65	11	20	4	-	-	Tr	Tr	Tr^C
96	L1-125		82	13	3	2	-	Tr	-	-	
97	L1-305	60	90	1	6	2	-	-	Tr	Tr	Tr^Q, Tr^C
98	L1-304	61	90	-	6	1	0.5	-	0.5	-	1.5^S
99	L1-299	60	95*	*	*	*	*	-	*	*	$*^S$
100	L1-300	65	95*	1*	3*	-	-	-	1*	*	
101	L1-382	50	59	17	8	6	5	3	Tr	1	
102	L1-383	61	65	10	7	18	-	-	Tr	-	
103	L1-301	62	95*	-	3	*	-	-	*	-	
104	L1-302										
105	L1-303	60	86	4	5	4	Tr	-	Tr	-	1^C
106	L1-126		65	11	18	6	-	0.5	-	-	0.5^Q
107	L1-127	66	37	20	30	11	-	Tr	-	-	$1^Q, Tr^C$
108	L1-134	60	92	2	5	1	-	Tr	Tr	Tr	
109	L1-133		76	4	16	4	-	-	0.5	0.5	
110	L1-132										
111	L1-131	56	92	2	3	1	0.5	Tr	0.5	Tr	Tr^Q
112	L1-136	58	85	3	8	2	1	-	1		
113	L1-135	55	68	8	23	Tr	Tr	-	1	Tr	
114	L0-T-19	55	66	1	32	1	-	-	-	-	
115	L0-T-18	61	90	3	2	2	-	-	Tr	Tr	1^Q
116	L0-T-17										
117	L0-T-16										
118	L0-T-15										
119	L0-T-14										
120	L0-T-13										
121	L0-T-12										
122	L0-T-11										
123	L0-T-10										
124	L0-T-20		67	1	4	12	11	-	Tr	Tr	$3^C, 1^Q$
125	L0-T-21	50	55	13	1	12	17	-	4	0.5	
126	L0-T-22	45	64	-	14	2	16	-	3	Tr	$1^Z, Tr^Q$
127	L0-T-25	58	83	4	11	1					
128	L0-T-26	56	70	8	22	1	-	-	Tr	Tr	
129	L0-T-27	55	75	16	7	1	-	-	Tr	Tr	Tr^C
130	L0-T-28		90	8	-	1	-	Tr	Tr		
131	L0-T-29	55	94	2	-	1	-	1	Tr		Tr^C
132	L0-T-30	61	89	Tr	8	2	1	-	Tr		
133	L0-T-31	59	90	-	9	-	0.5	-	Tr	Tr	Tr^O
134	L0-T-32	61	97	-	1	Tr	Tr	-	Tr	-	2^O
135	L1-371										
136	L1-370										
137	L1-380	58	69	2	8	22	-	-	1	Tr	
138	L1-381	45	45	31	3	14	2	2	Tr	1	Tr^C

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
139	L1-353	54	60	23	Tr	10	1	3	Tr	Tr	1^{Q}
140	L1-354	55	58	11	1.5	28	Tr	-	Tr	-	0.5^{Q}
141	L1-360	58									
142	L1-359	54	82	4	3	11	-	0.5	Tr	-	0.5^{Q},Tr^{C}
143	L1-362										
144	L1-369	61	92*	Tr	5	3	Tr	-	Tr	-	
145	L1-372	60	82	Tr	12	3	-	-	Tr	-	3^{O}
146	L1-379	59	80	Tr	8	9	Tr	-	Tr	-	3^{S}
147	LO-T-33										
148	LO-T-34										
149	LO-T-35	59	97*	Tr*	1*	Tr*	1*	-	1*		
150	LO-T-40										
151	LO-T-41										
152	LO-T-42										
153	LO-T-43										
154	LO-T-45	51	55	6	3	14	15	Tr	3	2	2^{Q}
155	L2-91	55	90*	3*	3*	1.5	1.5	-	Tr	Tr	
156	L2-92	55	62	3	28	7	-	-	Tr	-	
157	LO-T-39	56	81	7	9	3	Tr		Tr		0.5^{Q}
158	LO-T-36	62	94	3	2	-	0.5	-	0.5		Tr^{Q}
159	LO-T-37	60	93	1	0.5	5	0.5	Tr	Tr		Tr^{Q}
160	LO-T-38										
161	L2-93	59	91	4	5	Tr	-	-	Tr	Tr	
162	L2-90		80	9	9	2	Tr	-	Tr	0.5	
163	L2-88	55	81	8	2	3	3	-	2	-	1^{Q}
164	L2-101	51	67	17	3	7	4	-	0.5	Tr	1.5^{Q},Tr^{Z}
165	L2-87		60	-	10	1	20	-	3	Tr	6^{Q},Tr^{Z}
166	L2-86	55	65	15	-	6	10	-	1	2	1^{Q},Tr^{Z}
167	L2-89		65	1	24	2	5	-	1.5	Tr	1^{Z}
168	L2-99	56	70	13	15	2	-	-	Tr	Tr	
169	L2-95	60	90*	3*	3*	3*	1*				
170	L2-94	60	86	2	4	2	5	-	1	-	
171	L1-378	63	88	4	2	4	1	-	Tr	-	Tr^{Q},Tr^{C}
172	L1-373	63	98*	Tr*	Tr*	Tr*	-	-	Tr	-	Tr^{O}
173	L1-368	59	95*	-	3*	2*	Tr*	-	Tr*	-	
174	L1-363	54	94	4	Tr	2	Tr	-	Tr	-	Tr^{Q}
175	L1-358	61	87	5	1	6	-	1	Tr	-	
176	L1-355	58	70	12	6	6	1	5	0.5	0.5	
177	L1-356	58	62	20	2	13	Tr	1	Tr	-	2^{Q}
178	L1-357	60	31	41	1	24	1	-	Tr	-	1^{C}
179	L1-364	59	95*	Tr*	3*	2*	-	-	Tr	-	
180	L1-367	60	95*	Tr*	-	-	-	-	Tr	-	5^{S}
181	L1-374	62	95*	Tr	5*	-	-	-	Tr		
182	L1-377	66	80	-	12	8	Tr	-	Tr		
183	L2-96	62	95*	1*	4*	Tr	-	-	Tr		
184	L2-97	62	68	1	29	2	-	-	-	-	
185	L2-98	60	83	4	13	Tr	-	-	Tr	Tr	
186	L2-139	45	35	13	-	34	5	10	2	-	2^{Q},Tr^{C}

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
187	L2-138		77	9	7	2	3	-	2	-	1^{Q},Tr^{C}
188	L2-140	50	60	5	8	15	9	-	1	0.5	1^{Q},1^{C}
189	L2-145	57	62	15	5	11	5	-	2	-	0.5^{Q}
190	L2-146	53	70	4	14	3.5	6	-	1.5	-	1^{Q}
191	L2-147	56	86	4	7	1	Tr	-	1	Tr	1^{C},Tr^{Q}
192	L2-148	61	90*	2*	6*	1*	-	-	Tr		
193	L2-149	63	94	4	0.5	1.5	-	Tr	Tr	Tr	Tr^{Q},Tr^{C}
194	L2-150	58	82	2	13	2	-	-	Tr	-	1^{Q}
195	L2-151										
196	L2-152	61	90	Tr	8	0.5	1.5	-	Tr	Tr	1^{O}
197	L1-376	62	84	Tr	9	0.5	Tr	-	0.5	Tr	6^{O}
198	L2-153										
199	L1-375	62	95*	Tr	3*	1*	*	-	*		
200	L1-366	63	95*	1*	-	-	Tr	-	Tr	-	4^{S}
201	L1-113										
202	L1-365	60	92	Tr	2.5	4	-	-	0.5	-	1^{C},Tr^{S}
203	L1-112	56	90*	2*	4*	2*	-	-	Tr	-	2^{O}
204	L1-36	60	78	5	6	9	1	1	Tr	Tr	Tr^{Q}
205	L1-T-18	50	75*	Tr	-	25*	-	-	Tr		
206	L1-111	48	46	32	-	12	6	-	1	Tr	2^{Q}
207	L1-T-17	55	67	16	-	9	4	4	Tr	1	
208	L1-T-19	61	73	0.5	11	12	-	2.5	Tr	-	
209	L1-T-20	65	77	1	16	6	-	-	-	-	
210	L1-T-21	61	82	1	9	8	0.5	-	-	-	
211	L1-T-22	59	82	7	2	5	Tr	3	1	Tr	
212	L1-T-23	58	91	2	4	3	-	Tr	Tr		
213	L2-154	59	90*	2*	4*	3*	-	-	Tr	-	Tr^{C}
214	L2-155	58	85	6	7	2	-	-	Tr		
215	L2-156	61	92	Tr	8	Tr	-	-	Tr		
216	L2-157	59	82	1	12	1	Tr	-	1	Tr	3^{O}
217	L2-158	63	80	Tr	6	2	Tr	-	Tr	-	12^{O}
218	L2-161	62	75	2	20	3	-	-	Tr	Tr	
219	L2-162	58	58	3	36	3	-	-	Tr	Tr	Tr^{S}
220	L2-163	54	60	9	18	2	8	-	0.5	0.5	2^{C},S
221	L2-164	51	52	4	8	8	21	-	6	Tr	1^{Q}
222	L2-143	50	73	3	14	2	6	-	2	-	Tr^{Z}
223	L1-T-1	60	78	Tr	9	3	7	-	1	Tr	1^{Q}
224	L1-T-4	60	66	1	17	6	-	-	1	Tr	1^{Q},7^{O}
225	L1-T-3	59	82	6	9	1	-	-	2	Tr	Tr^{Q}
226	L1-T-4										
227	L1-T-5	59	92	4	-	0.5	-	5	0.5		
228	L1-T-6	59	98	1	-	1	-	-	Tr		
229	L1-T-7	58	86	-	13	1	Tr	-	0.5		
230	L1-T-8	60	98	-	1	0.5	Tr	-	Tr		
231	L1-T-9	58	83	0.5	13	2	-	-	0.5	-	1^{O}
232	L1-T-10	60	69	25	-	6	Tr	Tr	1		
233	L1-T-11	58	95	0.5	4	0.5	-	-	Tr		

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
234	L1-T-12	65	85	2	10	3	-	-	Tr		
235	L1-T-13	64	88	Tr	7	5	-	-	Tr		
236	L1-T-14	65	75	5	5	13	-	Tr	Tr		
237	L1-T-15	64	68	2	19	10	-	-	1		
238	L1-T-16	58	97	1	1	0.5	-	-	Tr		
239	L3-135	59	89	1	2	7	-	-	Tr	-	Tr^S,Tr^C
240	L3-134										
241	L3-133		75	6	4	11	Tr	4	Tr	Tr	
242	L1-23	56	81	4	Tr	9	-	5	Tr	-	1^Q
243	L1-169	61	70	3	15	11	-	-	Tr	-	1^Q
244	L1-168	61	96*	1	2*	1*	*	-	*		
245	L1-166	59	88	2	5	5	-	-	Tr	-	Tr^C
246	L1-165	63	95*	2*	-	-	-	-	1	-	1^S
247	L2-160	65	66	5	28	2	-	-	Tr		
248	L2-165	55	63	5	0.5	17	8	5	1	0.5	
249	L2-168		85	4	3	Tr	6	-	2		
250	L2-166	55	57	26	1	16	Tr	-	Tr		
251	L1-75										
252	L1-148	60	84	7	5	1	3	-	Tr		
253	L2-170										
254	L2-169	55	84	10	1	1	2	-	-	-	2^C
255	L2-159	60	80	7	10	2	-	-	Tr	-	1^C
256	L2-178	59	95*	1*	3*	1*	-	-	1*		
257	L2-179	59	95*	2*	2*	0.5*	-	-	0.5*		
258	L2-180	59	70	Tr	-	13	7	-	Tr	-	10^O
259	L2-181										
260	L2-182	61	92	1	2	Tr	-	-	Tr	-	5^O
261	L1-164	60	95*	Tr	4	Tr	-	-	Tr		
262	L1-172	58	76	3	-	20	Tr	-	1	Tr	
263	L1-170	63	89	9	-	1	-	Tr	Tr		
264	L1-171	55	66	1	22	12	-	-	Tr		
265	L1-43	57	70	12	4	13	-	-	Tr		
266	L1-41	54	68	16	3	12	Tr	-	Tr	Tr	
267	L1-44										
268	L1-45										
269	L1-161	61	83	2	4	9	-	-	Tr	-	2^C
270	L1-160	54	73	3	3	21	-	-	Tr	-	Tr^C
271	L1-159										
272	L1-158	62	90	3	Tr	2	-	6			
273	L1-173	51	60	8	19	15	-	Tr			
274	L2-183	60	88	0.5	5	2	0.5	-	0.5	-	3^O
275	L1-89	64	90*	2*	4*	2*	2*	-	*		
276	L1-94	65	90*	*	8*	1*	-	-	1*		
277	L1-95										
278	L1-81	52	37	20	30	11	Tr	-	1	Tr	
279	L1-82										
280	L1-84										

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
281	L1-83										
282	L1-85	56	75	10	9	3	Tr	1	Tr	Tr	
283	L2-175										
284	L2-176										
285	L1-88	64	88	Tr	9	2	1	-	Tr	Tr	
286	L1-89	64	90*	2*	5*	2*	*	-	*		
287	L1-91		73	7	5	15					
288	L1-93	59	95*	*	3*	1*	-	1*			
289	L1-92	55	75	1	-	21	-	3			
290	L1-325	58	61	4	17	16	4				
291	L2-1	59	88	Tr	6	5	Tr	Tr	Tr		
292	L1-323	55	72	3	16	7	2	-	Tr	0.5	
293	L1-324										
294	L1-322	58	74	9	2	6	-	8	Tr	Tr	
295	L1-157	64	42	12	10	26	-	10	0.5	0.5	
296	L1-156	57	73	11	10	5	-	1	1		
297	L1-162	65	85	1	9	5	-	-	Tr		
298	L1-152	52	90*	4*	-	4*	-	2*			
299	L1-153	63	64	9	16	11	-	-	Tr		
300	L1-155										
301	L1-333	59	84	5	4	6	-	Tr	Tr		
302	L1-334	61	75	4	8	8	-	5	Tr		
303	L1-342	58	73	1	2	24	-	-	Tr	-	Tr^{C}
304	L1-341	58	71	2	19	8	-	Tr	Tr		
305	L1-338										
306	L1-339	55	77	0.5	1	21.5	-	-	Tr		
307	L1-340		52	16	11	13	9	-	Tr	Tr	
308	L1-343	60	95*	1*	3*	1*					
309	L1-344	58	81	3	-	16					
310	L1-331		65	22	-	10	-	3	-	Tr	
311	L1-330	58	60	8	3	13	-	12	0.5	3.5	
312	L1-319		71	7	3	5	11	-	1.5	1.5	
313	L1-320										
314	L1-349	52	65	10	-	18	1	2.5	0.5	-	3^{Q}
315	L1-348	57	80	4	5	10					
316	L1-347	60	74	5	19	1	-	1	Tr		
317	L1-346	54	58	13	5	16	-	6			
318	L1-181	55	83	4	3	7	3	Tr	0.5	Tr	
319	L1-182	56	59	2	14	13	10	-	2	Tr	1^{S}
320	L1-183	59	71	12	2	12	0.5	1	0.5		
321	L1-184	60	85*	1*	9*	6*					
322	L1-185		52	17	1	11	13	Tr	5	Tr	2^{Q}
323	L1-186	54	57	7	6	18	7	2	8	Tr	Tr^{Z}
324	L1-211	55	66	-	9	6	8	-	12	Tr	
325	L1-210		59	9	4	18	6	-	3	-	1^{Q}
326	L1-209	57	57	14	5	21	-	2	Tr		
327	L1-208	56	57	18	-	24	-	0.5	-	-	0.5^{C}
328	L1-207	60	67	5	Tr	17	-	11			

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
329	L1-206	59	57	18	4	11	-	8	Tr	1	1^Q
330	L1-205	51	62	20	-	9	5	1	1	1	2^Q
331	L1-196	58	64	11	0.5	22	-	2.5	Tr	-	
332	L1-195										
333	L1-194	66	80	5.5	3	11.5	-	0.5	Tr		
334	L1-193	55	82	2	9	5	-	2	Tr	Tr	
335	L1-192	58	79	8	-	8	0.5	3	0.5	-	1^Q
336	L1-189	66	68	4	4	20	2	-	1	Tr	
337	L1-203										
338	L1-188										
339	L1-187	50	59	17	-	13	9	-	2	1	
340	L1-200										
341	L1-201										
342	L1-202	60	48	--	20	16	8	Tr	3	Tr	6^O
343	L1-221	59	55	17	Tr	18	6	Tr	4	Tr	
344	L1-222	55	54	4	5	19	14	-	4	Tr	Tr^Z, Tr^C
345	L1-223										
346	L3-115										
347	L3-114	55	84	2	-	8	-	6	Tr		
348	L3-113	55	72	8	3	14	-	3	-	-	
349	L3-116	57	54	22	3	20	Tr	1	Tr	Tr	
350	L3-117		74	7	-	17	-	2			
351	L3-118		63	17	-	15	3	Tr	1		
352	L3-119	58	95*	2*	-	1*	--	2*			
353	L1-225	44	71	5	-	12	-	10	Tr	1	
354	L1-226	60	65	10	9	13	-	3	Tr	0.5	
"	L1-227	58	84	11	-	1	-	4	Tr	Tr	
355	L1-228	56	80	7	-	10	-	3	Tr		
356	L1-229	58	76	6	-	16	-	1	Tr	--	1^C
357	L3-120		62	6	-	25	-	6	Tr	1	
358	L2-39	58	97*	--	-	--	-	3	-	--	
359	L2-40	58	67	3	-	17	-	14	Tr		
360	L2-38										
361	L2-37	59	69	10	--	16	-	5	Tr	Tr	
362	L2-36										
363	L2-35										
364	L2-34										
365	L2-30										
366	L2-31										
367	L2-32										
368	L2-33										
369	L2-3	53									
370	L2-4	55	80	1	-	8	-	11	Tr	Tr	Tr^Q
371	L2-2		85	-	-	4	-	10	-	-	Tr^Q
372	L2-5	64	72	-	-	24	-	3	Tr	0.5	Tr^Q
373	L2-6	51	63	5	-	30	-	2	Tr	Tr	
374	L2-8	54	87	3	-	3	Tr	5	1	Tr	$1^Q, Tr^Z$
375	L2-10	45	62	-	-	23	-	14	Tr	1	Tr^Q

TABLE B-1 (cont'd.)

Lab No.	Field No.	An.	Plag.	Scap.	Pyx.	Amph.	Gt.	Ep.	Opq.	Sph.	Others
376	L2-12	48	83	1.5	-	7	-	7	0.5	Tr	1^{Q}
377	L2-13		31	-	-	57	-	9	2	1	1^{Q}
378	L2-15		56	13	-	26	3	2	Tr	Tr	
379	L2-23	48	69	10		12	Tr	3	Tr	1	5^{Q}
380	L2-24		56	Tr	-	30	-	8	Tr	6	Tr^{Q}
381	L2-25	44	75	-	-	16	-	6	Tr	1	2^{Q}
382	L2-27		46	11	Tr	34	3	3	Tr	0.5	2^{Q}
383	L2-26	48	66	-	-	15	-	16	Tr	2	Tr^{Q}, Tr^{2}

TABLE B-2

METASOMATISED GNEISSES

Lab No	Field No	Qtz	Plag	Kspar	Cpx	Opx	Hble	Bio	Gt	Op	Sph	Others
401	L3-79	Tr	67	-	1	8	13	1	8	2	1	Tr^Z
409	L3-59	20	26	-	9	-	18	Tr	21	5		
415	L3-4	*	*	-	*	-	*	-	*	*	*	Tr^Z
425	L3-77	39	36	Tr	1.5	-	11	-	5	7	Tr	1^Z
426	L3-28	6	41	-		-	43	*	1	8	-	1^Z
427	L3-46	13	17	-		-	37	9	15	6	-	
428	L3-8	21	14		Tr	-	51	-	9	3	1	Tr^Z
429	L3-54	2	35	-	26	5	18	-	11	4		
452	L1-269	9	66	-		-	13	10	1.5	0.5		
453	L3-143		← 43 →		18	-	8	-	23	7	-	1^Z
454	L3-42	3	21	-	29	-	14	-	20	12		1^Z
455	L3-154	*	*	-	*	-	*	-	*	*		*Z
465	L3-68	13	37	14	9	-	5	-	16	6		
475	L1-352	20	42	10	Tr	-	19	-	4	5		
476	L1-278	← 47 →		-	24	-	8	-	13	7	1	
477	L3-129	16	35	-	12	-	10	-	21	5	Tr	1^Z
478	L3-127	← 30 →		-		-	26	-	32	7	2	3Z
480	L3-105	*	*	*	*	-	*	-	*	*		
481	L3-104	53	32	1	5	2	5	-	Tr	2		
482	L3-102	5	27	-	18	2	20	-	16	8	4	
483	L3-100	Tr	58	-	27	-	3	-	7	5		Tr^Z
493	L3-84	Tr	46	-	21	10	3	-	16	4		
494	L3-94	35	20	-	6	-	6	-	21	10	0.5	1^Z
495	L3-95	13	49	-	5	16	15	-	0.5	2		
496	L3-90	4	69	Tr	6	13	5	-	-	3	--	
497	L3-91	13	36	4	14	-	7	-	20	7	0.5	
498	L3-93	*	*	-	*	-	*	-	*	*	*	
504	L2-84	-	57	-	5	5	23	-	6	4		
518	L1-328	7	54	7	17	-	3		2	10		Tr^Z
519	L1-96	29	30	-	Tr	-	13	-	22	4	1	
521	L1-337	5	50	8	19	-	3	-	8	7		
552	L2-109	10	30	-	25	25	Tr	-	7	3		
553	L2-83	-	36	-	30	6	3	-	18	7		

TABLE B-3.

AMPHIBOLITES & AMPHIBOLE-PLAG. GNEISS (WITHOUT K-SPAR)

Lab No	Field No	Qtz	Plag	Kspar	Cpx	Opx	Hble	Bio	Gt	Op	Sph	Others
403	L0-26	-	26		-	-	69	Tr	4	1	0.5	Tr^{Z}
⊙ 404	L0-12	-	22		17	-	40	-	18	3	-	0.5^{Z}
412	L3-53	-	39		-	-	50	6	-	2	3	
-414	L3-55	12	56		-	-	19	12	1	Tr	-	Tr^{C}
418	L3-22	7	40		-	-	50	3	-	Tr	-	
-419	L2-42	-	24		-	-	60	Tr	11	Tr	2	Tr^{C}
·421	L3-159	*	*		-	-	*	-	*	*		
422	L3-158	2	17		6	-	64	-	5	4	0.5	1.5^{Z}
⊙ 423	L3-157	*	*				*		*	*		*^{Ep}
⊙ 457	L3-149	*	*		*	*	*	-	*	*	*	
-461	L3-19	2	40		-	-	44	11	-	3	-	
468	L2-61	2	22		-	-	73	-	2	1	Tr	
469	L2-58	-	25		-	-	71	-	4	Tr		
471	L2-48	-	43		-	-	47	Tr	8	Tr	2	Tr^{Ep}
⊙ 473	L1-350	0.5	18		8	4	63	-	4	3	-	
⊙ 474	L2-199	Tr	22		-	2	65	-	8	3	-	Tr^{Z}
-479	L1-279	-	57				36	2	4	1		
-485	L3-98	0.5	61		-	-	37	3	-	0.5	-	Tr^{Scap}, Tr^{Z}
499	L0-66	5	63		5	12	12	-	Tr	2.5	-	
506	L1-21	Tr	29		-	-	64	7	Tr	Tr	Tr	
⊙ 511	L1-22	-	12		6	-	67	-	15	Tr	-	
-513	L2-144	10	81		-	3	5	-	0.3	0.6		0.3^{Z}
516	L1-69	-	6		42	-	5	-	9	1	3	4^{C}, 29^{Scap}
517	L1-70	2	20		16	-	58	-	-	2	2	
-522	L1-55	-	*		*	-	*	-	*	1	*	*^{Scap}, *^{C}
-523	L1-58	-	*		*	-	*	-	*	*	-	
526	L2-29	-	30		9	-	60	-	-	1	-	
528	L2-21	-	*		-	-	*	*	-	-	*	
532	L2-28	11	15		-	-	66	4	Tr	3	-	1^{C}
·550	L3-88	4	67		-	-	25	3	-	1	-	

⊙ Coronite amphibolite

TABLE B-4

MIGMATITES & GRANITIC GNEISSES

Lab No	Field No	Qtz	Plag	Kspar	Cpx	Opx	Hble	Bio	Gt	Op	Sph	Others
400	L3-87	27	42	14	–	–	–	16	0.5	0.5	Tr	
402	L3-80	25	25	25^{M}	–	–	20	5	–	–	1	
405	L3-61	20	60	–	–	–	18	2	–	0.2	–	
406	L3-81	7	56	7	4	–	9	15	3	Tr	–	
407	L3-1	33	32	29	–	–	1	4	Tr	10	Tr	
408	L3-2	36	37	–	–	–	–	15	–	–	1	15^{Ep}
410	L3-58	13	65	6	Tr	–	8	6	0.5	–	–	Tr^{C},Tr^{Z}
411	L3-52	35	60	–	–	–	–	5	–	–	Tr	
416	L3-6	35	35	15	–	–	1	10	3	1	–	
417	L3-21	36	40	2	–	–	8	8	2	3	1	Tr^{Z}
420	L2-44	38	42	5^{M}	–	–	–	15	–	Tr	Tr	Tr^{C}
424	L3-155	*	*	*^{M}	–	–	*	*	*	*	*	
456	L3-153	←	87	→	–	–	–	10	3	Tr	–	
458	L3-160	*	*	*^{M}	–	–	–	*	*	*	–	
462	L3-16	30	50	15	–	–	–	5	–	Tr	–	1^{Ep}
463	L3-18	20	59	–		–	4	15	–	0.5	Tr	
466	L2-72	*	*	*	*	–	*	–	*	*		
467	L2-63	30	30	30	–	–	5	2	3	Tr	–	Tr^{C}
470	L2-57	38	38	5^{*M}	–	–	–	15	–	1	3	
472	L2-69	*	*	*^{M}	–	–	–	*	–	–	*	
484	L3-99	19	43	21	–	2	13	2	–	0.5		
486	L0-1	20	65	5	–	–	–	10	Tr	–	–	
487	L1-400	*	*	*		–	*	*		*	*	
491	L3-123	←	90	→	–	–	2	8	Tr	Tr	–	
492	L1-240	7	71	7	2	4	2	Tr	Tr	1	–	
501	L0-60	*	*	*	*	*	*	–	–	*		
505	L1-35	20	45	Tr	10	–	3	–	20	2	–	
507	L1-20	*	*	*	–	–	–	*	–	–	–	
508	L1-110	*	*	*	*	–	*	–	*	*	–	
509	L1-12	35	40	Tr	–	–	–	20	5	–	–	
510	L3-132	*	*	*		–	*	*	–	*	*	*^{Z}
512	L3-136	←	87	→	–	–	8	2	–	1	0.5	1^{Ep}
514	L1-30	20	65	4	–	–	10	Tr	1	1	–	
515	L1-68	*	*	*	–	–	*	*	–	–	–	Tr^{Z}
520	L1-102	*	*	*	–	–	–	*	*	*		
525	L3-112	35	35	20	–	–	8	2	–	0.1	–	
527	L2-7	30	40	4	–	–	14	7	4	Tr	0.5	
529	L2-14	32	32	7	–	–	21	Tr	5	1	Tr	
530	L2-16	48	48	–	–	–	–	4	–	–	Tr	
531	L2-17	27	32	–	–	–	25	12	3	0.5	0.5	
533	L2-22	30	30	26	–	–	7	7	–	Tr	Tr	