A Study of the Rare Earth Element Geochemistry and Mineral Chemistry of the Anorthosites and Related Rocks near Pleasant Bay, Cape Breton Island, Nova Scotia

by

Paul L. Mitchell

Submitted in partial fulfillment of the requirements for a Bachelor of Science (Honours) Degree

at

Dalhousie University Halifax, Nova Scotia March, 1979



DEPARTMENT OF GEOLOGY DALHOUSIE UNIVERSITY HAUFAX, NOVA SCOTIA CANADA B3H 4J1

#### DALHOUSIE UNIVERSITY, DEPARTMENT OF GEOLOGY

B.Sc. HONOURS THESIS

Author: Paul L. Mitchell

<u>Title</u>: A Study of the Rare Earth Element Geochemistry and Mineral Chemistry of the Anorthosites and Related Rocks near Pleasant Bay, Cape Breton Island, Nova Scotia

Permission is herewith granted to the Department of Geology, Dalhousie University to circulate and have copied for non-commercial purposes, at its discretion, the above title at the request of individuals or institutions. The quotation of data or conclusions in this thesis within 5 years of the date of completion is prohibited without the permission of the Department of Geology, Dalhousie University, or the author.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the authors written permission.

Date: March 19,1979

Copyright 1979

# **Distribution License**

DalSpace requires agreement to this non-exclusive distribution license before your item can appear on DalSpace.

# NON-EXCLUSIVE DISTRIBUTION LICENSE

You (the author(s) or copyright owner) grant to Dalhousie University the non-exclusive right to reproduce and distribute your submission worldwide in any medium.

You agree that Dalhousie University may, without changing the content, reformat the submission for the purpose of preservation.

You also agree that Dalhousie University may keep more than one copy of this submission for purposes of security, back-up and preservation.

You agree that the submission is your original work, and that you have the right to grant the rights contained in this license. You also agree that your submission does not, to the best of your knowledge, infringe upon anyone's copyright.

If the submission contains material for which you do not hold copyright, you agree that you have obtained the unrestricted permission of the copyright owner to grant Dalhousie University the rights required by this license, and that such third-party owned material is clearly identified and acknowledged within the text or content of the submission.

If the submission is based upon work that has been sponsored or supported by an agency or organization other than Dalhousie University, you assert that you have fulfilled any right of review or other obligations required by such contract or agreement.

Dalhousie University will clearly identify your name(s) as the author(s) or owner(s) of the submission, and will not make any alteration to the content of the files that you have submitted.

If you have questions regarding this license please contact the repository manager at dalspace@dal.ca.

Grant the distribution license by signing and dating below.

Name of signatory

Date

## TABLE OF CONTENTS

ABSTRACT	Page iii
LIST OF FIGURES	v
LIST OF TABLES	vii
CHAPTER 1: Introduction	1
Location and Access	1
Problem	l
Previous Work	6
CHAPTER 2: Field Work	9
General Field Work	9
Field Relations	10
CHAPTER 3: Petrographic Description	14
CHAPTER 4: Whole Rock Geochemistry	19
Major Element Composition	19
Rare Earth Element Analysis	22
CHAPTER 5: Mineral Chemistry	28
Determination of Plagioclase Compositions	28
Compositional Analysis of Coexisting Pyroxenes	28
CHAPTER 6: Discussion	34
Plagioclase Composition Variation	34
Pyroxene Geothermometry	36
REE Modelling of the Anorthosite Parent Magma	41
REE Contents of Country Rock Samples PM-2-4 and PM-2-9	50
Origin of the An <sub>or</sub> thosite	53
CHAPTER 7: Conclusions and Recommendations	55
ACKNOWLEDGEMENTS	57

REFERENCES	Page 58
APPENDICES	63
l: Petrographic Descriptions	63
2: Analytical Methods	84

#### ABSTRACT

The anorthosites and related rocks of this study are located about 5 kilometres east of the village of Pleasant Bay, Cape Breton Island, Nova Scotia. The anorthosites outcrop as a thin (~900m), northeast-trending lens with smaller lenses also found outside the main body. The country rock consists mainly of gneiss, amphibolite, schist, gabbro and granitic intrusions with some diabase and aplite dykes cutting both the anorthosite and the country rock. The contact between the anorthosite and the country rock is not well known but there are some fault contacts noted and a mylonite zone is present on the southeast boundary of the main anorthosite lens.

The current study examines three main facets of these rocks. A study of the composition of the plagioclase in the anorthosite was made to determine if any regular variation in the anorthite content in the plagioclase occured. It has been found that the anorthite content does change but in an irregular manner, perhaps due to localized metamorphic effects or shearing of an originally heterogeneous anorthosite body.

Associated with the anorthosite are gneissic rocks containing coexisting Ca-rich and Ca-poor pyroxenes and their compositions have been used as a geothermometer. The equilibration temperature for the pyroxenes is calculated to be between 870-930°C, in the pyroxene-granulite subfacies of regional metamorphism. This high grade of metamor-

iii

phism has not previously been reported in this area.

The rare earth element (REE) content of the anorthosite was also examined in an attempt to calculate the nature of the parent magma. The anorthosite has a very low total REE content with a positive Eu anomaly. The calculated parent magma has a relatively enriched and less fractionated REE content. A comparison of the chondrite-normalized REE pattern for the calculated parent magma was made with the patterns developed by tholeiites, andesites and alkali basalts. The results of this comparison seem to indicate that the original parent magma of the anorthosite may have had a tholeiitic composition.

Textural features in the anorthosite, such as granulation of crystals, faulted contacts with the country rock and irregularly dispersed plagioclase compositions, and an associated mylonite zone all seem to indicate that the anorthosite was tectonically emplaced into its present position. Since the anorthosite is associated with a granulite gneiss, it was probably emplaced from depth as most of the country rock around the anorthosite has only been metamorphosed to greenschist-amphibolite facies.

iv

#### LIST OF FIGURES

- Fig. 1: Comparison of the mapping of the Cape Breton Anorthosite by various authors and the location of the study area.
- Fig. 2: Photograph of fault contact between anorthosite and country rock along the Cabot Trail.
- Fig. 3: Geology map of the study area.
- Fig. 4: Irregular epidote banding in the anorthosite.
- Fig. 5: Chondrite-normalized REE distribution of the anorthosite samples.
- Fig. 6: Chondrite-normalized REE distribution of the mylonite (PM-2-9) and an amphibolite (PM-2-4) near the anorthosite.
- Fig. 7: Plot of the An-Ab-Or content of ten samples from the study area.
- Fig. 8: Plot of the compositions of the coexisting pyroxenes of sample K15-0530 in the system CaSi0<sub>3</sub>-MgSi0<sub>3</sub>-FeSi0<sub>3</sub>.
- Fig. 9: Variation of the plagioclase An content in the main anorthosite.
- Fig.10: Plot of the  $K_{\rm D}(\mbox{Mg-Fe})$  between the coexisting pyroxenes of sample K15-0530.
- Fig. 11: Temperature (CaSi0<sub>3</sub>-MgSi0<sub>3</sub>-FeSi0<sub>3</sub>) diagram for naturally occurring pyroxene assemblages at pressures less than 5 kilobars and the plot of the coexisting pyroxenes of sample K15-0530.
- Fig. 12: Chondrite-normalized patterns for the calculated parent magma of the anorthosite, a liquid in equilibrium with the anorthosite after 50 percent fractionation and the average of samples PM-1-1 and PM-2-3A.

- Fig. 13: Comparison of the REE chondrite-normalized patterns of the anorthosite parent magma, an average tholeiite and the average of 4 Archean tholeiites.
- Fig. 14: Comparison of the REE patterns of the anorthosite parent magma, an average alkali basalt and two Chilean andesites.
- Fig. 15: Comparison of the REE patterns of the amphibolite PM-2-4, an Archean tholeiite, an average tholeiite and a Chilean andesite.
- Fig. 16: REE patterns for the mylonite (PM-2-6), an average tholeiite and two Chilean andesites. A field for the REE content of calc-alkaline, shoshonite and alkali rocks of island arcs is also shown.

#### LIST OF TABLES

- Table 1: Major element chemistry of three anorthosites and two country rock samples from the study area.
- Table 2: Normative mineralogy of the anorthosite samples.
- Table 3: REE content (ppm) of the Cape Breton anorthosite and surrounding country rock.
- Table 4: Chondrite-normalized values for the anorthosite and country rock samples REE contents.
- Table 5: Chemical analyses of feldspars from anorthosites and country rocks.
- Table 6: Pyroxene analysis from sample K15-0530.

#### CHAPTER 1 INTRODUCTION

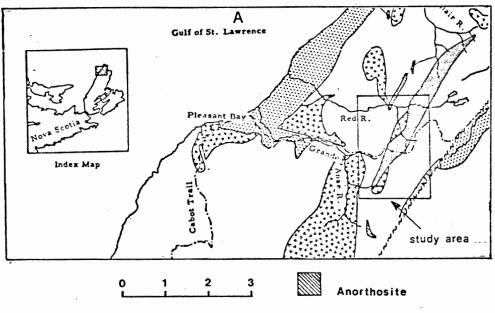
#### Location and Access

Outcrops of massif-type anorthositic rocks (Neale, 1964; Jenness, 1966) are located in northern Cape Breton Island, approximately nine kilometres east of the village of Pleasant Bay (Inverness Co.) on the Gulf of St. Lawrence (Map 1 - National Topographic Series 11 K/15) (Fig. 1). The main portion of the study area lies within the Cape Breton Highlands National Park and some outcrops are found up to one kilometre past the northern boundary of the Park (Map 1). The anorthosite is located near the level summit of the Cape Breton Highlands between 300 and 450 metres above sea level, and most outcrops are found along steep-sided streams (Grande Anse River, Red River) where thick bush often makes travel extremely difficult. The Cabot Trail also passes through the study area and is the only highway access to the anorthosite. Away from the streams and the Cabot Trail, however, thick glacial till deposits, dense forests and numerous bogs conceal the anorthosite.

#### Problem

Anorthosites were first mentioned in the literature by A.G. Werner in 1780, and the controversy over their origin has not yet been resolved. Anorthosites can be divided into three major classes based on their modes of origin. They are: (a) massif-type anorthosite, (b) layered intrusion-type anorthosite, and (c) intermediate-type anorthosite.

- 1 -



kilometres

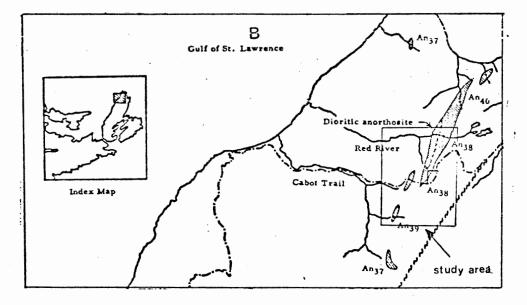


Figure 1. Location of the study area and comparison of the mapping of the Cape Breton Anorthosite between Neale (1964) (A) and Jenness (1966) (B). (Adapted from Jenness, 1966).

The massif-type anorthosite generally forms large plutonic intrusions consisting mainly of coarsely crystalline plagioclase. They usually are associated with a mangerite suite (quartz- and hypersthene-bearing rocks such as adamellites, charnockites, granites, quartz syenites) in Precambrian shield areas (notably the Grenville Province of the Canadian Shield). The layered intrusion-type anorthosites consist mainly of cumulate plagioclase crystals (often with cryptic layering) formed by differentiation processes in basic magma chambers or intrusions. Intrusions such as the Bushveld in South Africa, the Muskox in northern Canada and the Skaergaard in Greenland are prime examples of this type. The final class, the intermediate type, is, as the name suggests, of an origin intermediate between the first two. It has features similar to layered intrusions (some evidence of layering, relict igneous textures) and massif-type anorthosites (associated mangerite suites). Emslie (1970) describes such an anorthosite body, the Michikamau anorthosite, from the Nain Province of the Canadian Shield. Of these three types, the Cape Breton anorthosite most closely resembles the massiftype which will be discussed in further detail below.

Massif-type anorthosites (> 90 percent plagioclase; Buddington, 1939) form the largest gabbroic plutonic complexes, often with batholithic dimensions (Isachsen, 1966; Duchense and Demaiffe, 1978). They apparently only occur in mid-Proterozoic (1800-1000 million years) shield areas, usually in terrains of the upper amphibolite facies to granulite facies of regional metamorphism (Isachsen, 1966; Duchense and Demaiffe, 1978). Emplacement can be syn- or post-tectonic and

- 3 -

subsequent deformation and recrystallization (cataclastic textures, reduced anorthite contents from original calcic compositions, etc.) often affect the bodies (Duchense and Demaiffe, 1978).

Massif-type anorthosites can be subdivided into two major classes based on the plagioclase and iron-titanium oxide content (Anderson and Morin, 1966). The labradorite-type massif has a plagioclase range from An<sub>68</sub> to An<sub>45</sub> and titaniferous magnetite whereas the second class, the andesine-type, is characterized by plagioclase in the range of An<sub>48</sub> to An<sub>25</sub> and hemo-ilmenite oxides (Anderson and Morin, 1966). The andesinetype massif probably corresponds to the Adirondack-type massif as described by Buddington (1939). Both the labradorite- and andesinetype seem to be commonly associated with a mangerite suite (deWaard, 1966; Duchense and Demaiffe, 1978). Anderson and Morin (1966) also point out that massif-type anorthosites can be distinguished from anorthosites of layered intrusions by their greater homogenity and coarsegrained texture (grain sizes usually more than 1 centimetre).

Despite a considerable influx of new information on anorthosites (both field and experimental data) in the last few decades, the questions about their genesis and the nature of the parent magma remain very controversial. The composition of the parental magma has been suggested by various authors to range from basaltic to granodioritic. Recently, Duchense and Demaiffe (1978), Simmons and Hanson (1978) and others have analysed samples from massif-type anorthosites for trace elements and rare earth elements in an attempt to set limits on the compositions

- 4 -

and origins of their parent magmas.

The Cape Breton anorthosites, from compositional and textural considerations, seem to most closely resemble the andesine-type massif anorthosites. This anorthosite has, however, several interesting features not usually common to massif-type anorthosites that warrant further investigation.

These anorthosites are located in the Appalachian structural province which is much younger than the anorthosite-rich Grenville structural province some 500 kilometres to the northwest. Although no accurate ages for the Cape Breton anorthosite bodies are available, Jenness (1966) considers it to be approximately the same age as a similar body in Newfoundland (900  $\pm$  15 million years). He postulates that the Cape Breton anorthosites are, in fact, just outliers of the Grenville province and are not directly related to the Appalachian structural province.

The Cape Breton anorthosites are also unusual because they are located in a terrain which, according to Jenness (1966), has only been metamorphosed to the almandine-amphibolite facies and more commonly the greenschist facies. Jenness (1966) also notes that the associated mangerite suite appears to be missing in the case of these anorthosites.

Contact relations of the anorthosite with the surrounding country rock are not well known because of generally poor exposure. The best exposed contact is found on the Cabot Trail where the anorthosite appears

- 5 -

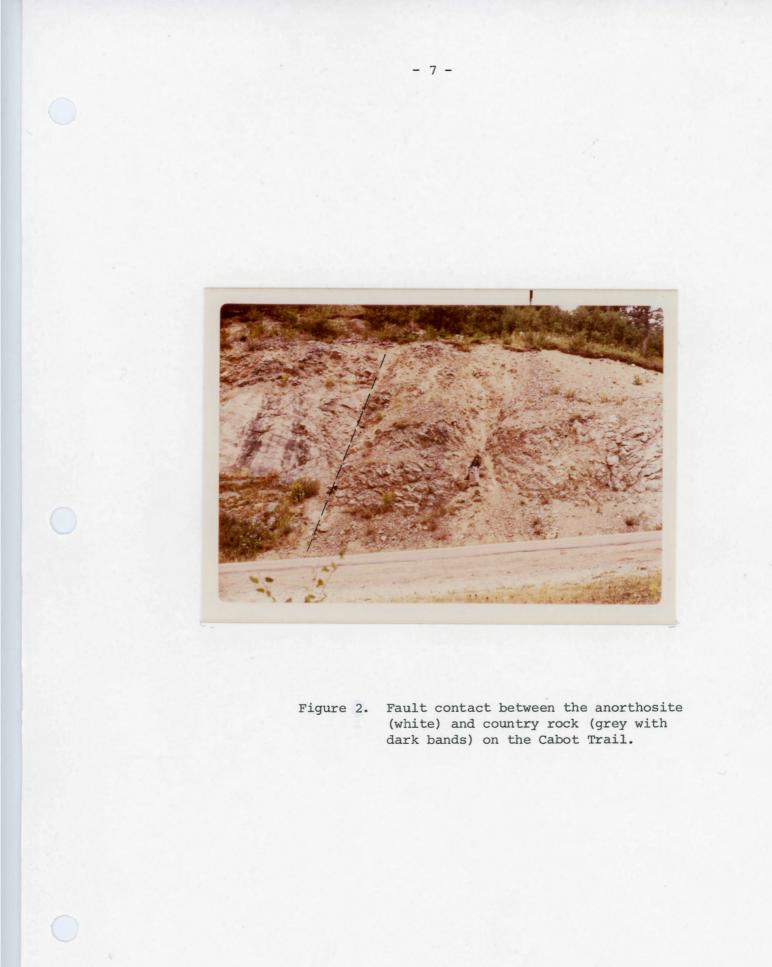
to be in a fault contact with surrounding metasediments or metavolcanics (Fig. 2). The general cataclastic nature of most of the anorthosite samples examined seems to indicate it was emplaced forcefully as a solid (or semi-solid) mass into the country rock.

The thesis will examine the rare earth element geochemistry of the anorthosite in order to estimate the nature of the parental magma. Rare earth element and whole rock (by electron microprobe) analysis of some surrounding country rock will be made in an attempt to relate the anorthosite to the country rock. Microprobe studies of the plagioclases in the anorthosite (and some country rock samples) will help establish chemical variations, if any, in the An content of the plagioclases. The plagioclase work may be useful in locating areas that have had a different igneous and/or metamorphic history from the rest of the anorthosite body. Coexisting pyroxenes in a gneissic rock near the anorthosite have also been examined by the microprobe and their compositions may add new information on the metamorphic history of the country rock. The presence of these pyroxenes is indicative of the granulite facies of regional metamorphism, a grade that has not previously been reported here.

#### Previous Work

The presence of anorthosite in Cape Breton was first noted by Neale (1956, 1964) who mapped it as two, northwest-trending, tabular bodies with several smaller lens-shaped inclusions in surrounding granitic rocks (Fig. 1). He provided very limited descriptive or petrologic data however.

- 6 -



Until the present time the most important study of the Cape Breton anorthosite was made by Jenness (1966). He used his own field data as well as those of Neale to complete a preliminary petrological and chemical study of the anorthosite and some surrounding country rock. His findings led to his remapping of the anorthosite bodies as originally proposed by Neale (1964) whereby he disregarded the large bodies and suggested the presence of several smaller lenses in their place (Fig. 1). Jenness (1966) noted the presence of both anorthosite and hornblende anorthosite (10-30 percent hornblende) in the study area, the absence of an associated mangerite suite and the relatively low grades of metamorphism (greenschist to amphibolite facies) of the anorthosite and surrounding country rock. He also presented different hypotheses as to the origin of the anorthosite but, with his limited data, was not able to arrive at any concrete conclusions.

The last study of these anorthosites was by Isherwood (1974). He studied a few specimens taken from a road cut along the Cabot Trail but due to the extreme alteration and small number of samples was unable to contribute any new or unexpected information towards the solution of the problem of the origin of the anorthosite.

- 8 -

#### CHAPTER 2 FIELD WORK

#### General Field Work

Field work for this thesis was carried out by a party from the Nova Scotia Department of Mines (N.S.D.M.) and by the author. The Nova Scotia Department of Mines field party consisted of Paul Smith and Alan MacDonald who carried out stream traverses during August 1978 on the eastern and southeastern tributaries of the Red River, and on the three eastern tributaries of the Grande Anse River just south of the Cabot Trail. Numerous samples of the anorthosite and surrounding country rock were obtained, with emphasis on the anorthosite and its variation.

During two days in early September, the author with the help of Dr. D.B. Clarke and S. Delahay made a stream survey of the southeastern tributary of the Red River (previously sampled by the N.S.D.M.). Samples were collected at various locations along the stream with emphasis on sampling where noticeable compositional or textural variations in the anorthosite occurred. Some samples were also collected from outcrops of the anorthosite along the Cabot Trail. Wet weather and cool temperatures during September created high water levels in the streams and made stream traverses and sampling difficult.

The samples collected by the Nova Scotia Department of Mines were kindly made available by Dr. J. Duncan Keppie and ten of these, located throughout the study area, were selected to be made into polished thin

- 9 -

sections for an electron microprobe study (Map 2). The samples collected by the author (Map 2) were slabbed for thin sections (one polished thin section for microprobe work) and five were crushed for neutron activation determination of the rare earth element content.

#### Field Relations

The anorthositic rocks of the study area were, as mentioned, first mapped by Neale (1964) a few kilometres west of the steeply-dipping Aspy fault (Fig. 1). Neale mapped the anorthosite as a single northeast-trending lens with an average width of about 1.5 kilometres and pinching out on a southern tributary of the Grande Anse River about one kilometre south of the Cabot Trail. The field work completed by the Nova Scotia Department of Mines in 1978 has lead to many revisions of Neale's work however (Map 2, Fig. 3).

The anorthosite is now mapped as a thinner (averaging 900 metres wide), more sinuous body also trending in a northeasterly direction. As well, several smaller sinuous lenses, from a few to several tens of metres wide and up to a kilometre in length have been mapped in the country rock near the main anorthosite lens. Contact relationships between the anorthosite lenses and the country rock are obscure and no new contact relationships have been recorded.

Stretching the entire length of the anorthosite lens, on its southeastern boundary, is a mylonite zone averaging 300 metres in width. At one point this mylonite zone cuts across and divides the main anortho-

- 10 -

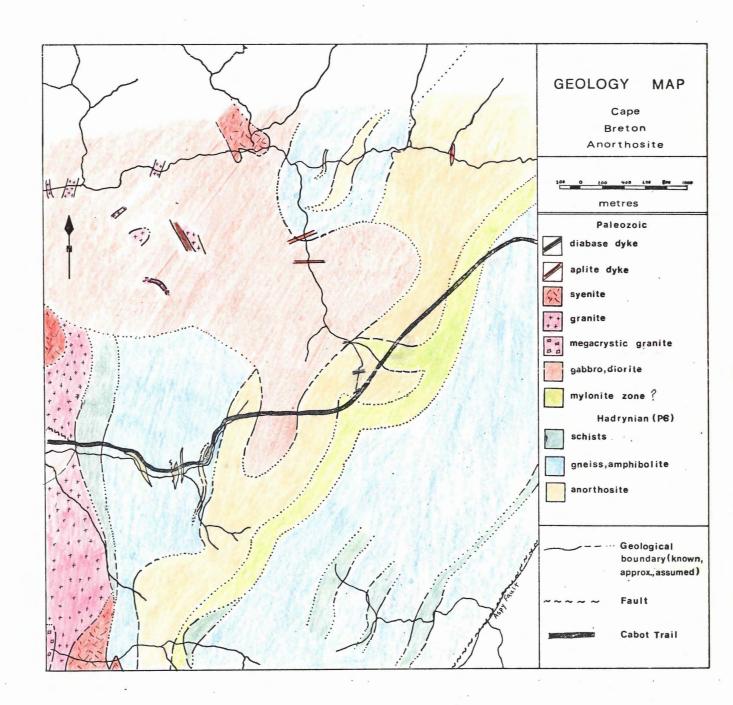


Figure 3. Geology map of the study area (from a map by P. Smith and Alan MacDonald of the Nova Scotia Department of Mines, 1979).

site lens. To the northwest and south of the mylonite zone the anorthosite is surrounded by gneisses (paragneisses according to Jenness, 1966), micaceous schists, marble and gabbro (dioritic to syenogabbroic composition) (Map 2). Granites of varying composition and characteristics (megacrystic granites, syenitic granites, etc.) are intrusive into the gneisses but they are not members of the mangerite suite complex that is usually found surrounding such massif-type anorthosites. All the above are intruded by small diabase and aplite dykes.

The anorthosite and gneisses are believed to be of a Hadrynian (1000-570 million years) age, although exact age relations between them have not been determined. The mylonite zone and the gabbro are believed to be Paleozoic in age (P. Smith, pers. comm., 1979) and a few of the intrusive granitic bodies near the study area have been dated; potassiumargon and rubidium-strontium give ages in the mid-Devonian range for granites in this area (Jenness, 1966) and are thus too young to have any relationship to a mangerite suite that might be associated with the anorthosite.

The gneisses and schists of the study area have been metamorphosed to the almandine-amphibolite facies (Neale, 1964; Jenness, 1966) and a gneissic rock closely associated with the anorthosite, ie, no fault contact is seen between the two, has been metamorphosed to upper granulite facies. Alteration minerals such as epidote, clinozoisite and chlorite in the anorthosite are indicative of the greenschist facies and, according to Jenness (1966), may represent a retrograde metamor-

- 12 -

phic event. The mylonite zone and cataclastic nature of some parts of the anorthosite indicate that dynamic metamorphism has also occurred.

In summary, the Cape Breton anorthosite is an andesine-type massif anorthosite outcropping as a thin northeasterly-trending lens (with smaller nearby lenses). Contact relations with the surrounding country rocks are obscure but granulation in the anorthosite may indicate forceful emplacement as a solid mass. The anorthosite and the gneisses are probably of a similar age (Hadrynian) but their interrelationship is unclear. These units are both intruded by gabbro and have been mylonitized, perhaps during the early Paleozoic. Devonian granitic rocks do not intrude the anorthosite but do intrude the gabrro and gneiss. Diabase dykes and aplite dykes are the youngest intrusives being found in all older rock types of the study area. The anorthosite, and most surrounding country rock, have undergone retrograde greenschist metamorphism.

#### CHAPTER 3 PETROGRAPHIC DESCRIPTIONS

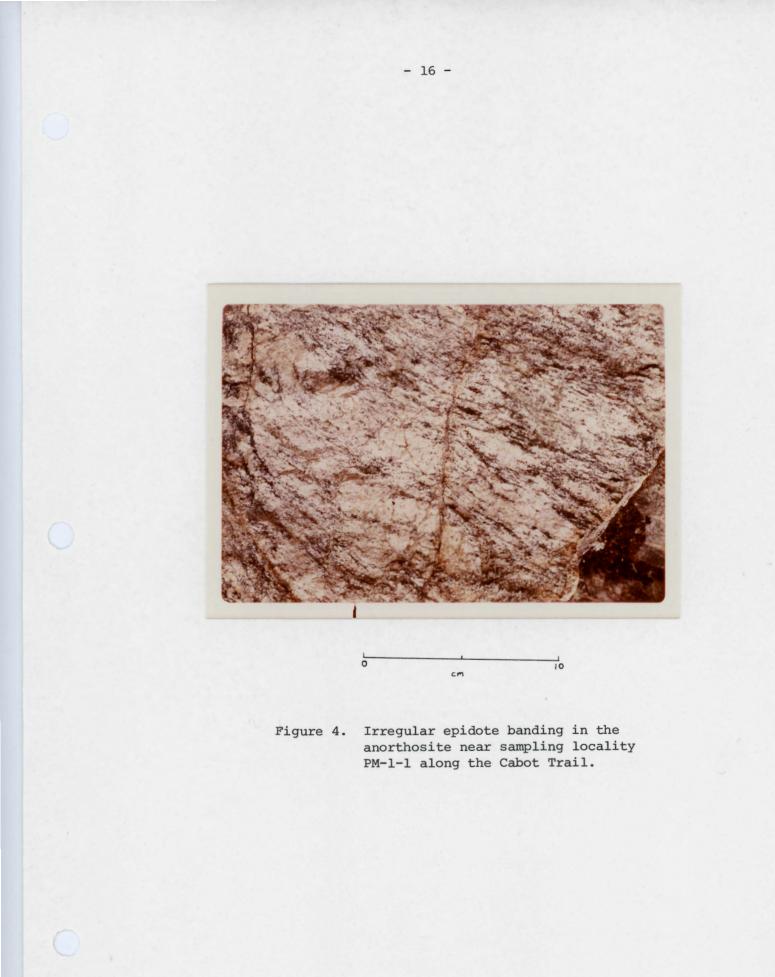
Samples were selected for thin sections from those collected by the Nova Scotia Department of Mines and the author. The samples were chosen in such a way as to cover the anorthosite body in the study area as completely as possible with particular emphasis on the variations in the anorthosite. A total of 40 samples were examined and 14 were selected for study and the bulk are from the anorthosite and hornblende anorthosites. A few thin sections are from random samples of the country rock around the anorthosite.

The anorthosites examined are mainly "true anorthosites" in that they contain more than 90 percent plagioclase. The anorthosites are usually hypidiomorphic granular with a medium grain size (from 1-2 mm). The individual plagioclase crystals are randomly oriented and are often granulated (sometimes quite extensively) as a result of cataclasis. This process has also caused the bending and kinking of the twin lamellae and the undulose extinction of some plagioclase crystals. The anorthite content of the plagioclases has been determined by the Michel-Levy method (maximum symmetry of extinction angles of twin lamellae) and by electron microprobe analysis. The anorthite content has been found to be in the andesine range from  $An_{35}$  to  $An_{49}$  with an average of approximately  $An_{43}$ . The lack of a regular pattern to the changing anorthite content in the anorthosite will be discussed in Chapter 6. Of the true anorthosites only a few contain more than 3-4 percent hornblende (usually chloritzed). Alteration minerals of the greenschist facies such as epidote, clinozoisite, zoisite, chlorite, carbonate and muscovite are widespread and usually account for 5-7 percent of the total mineral content of the anorthosites, but sometimes as high as 15-20 percent. Irregular banding of the epidote is sometimes found in the anorthosite (Fig. 4). Sericitization is by far the most common alteration of the plagioclase crystals and is so intense in some cases that it obscures grain boundaries and twin lamellae.

Closely associated with the true anorthosites are hornblende anorthosites, mapped previously (Neale, 1964; Jenness, 1966) as gabbroic anorthosites, which contain 15-25 percent green hornblende (often chloritized with a pale green color) and up to 70 percent plagioclase of andesine composition. The hornblende occurs in irregular bands up to 6 millimetres wide and opaques (magnetite) are associated with the hornblende, in some cases they account for 5-7 percent of the hornblende bands. Alteration minerals such as epidote and clinozoisite are generally less abundant in the hornblende anorthosites than in true anorthosites, but sericitization is just as common.

The spatial relationship between the hornblende and true anorthosites is not clear, but it appears that the hornblende anorthosites occur as randomly scattered lenses in the anorthosite bodies. These lenses appear more frequently near the anorthosite contacts with the surrounding gabbros and gneisses but the exact nature of this relationship is obscure.

- 15 -



Three thin sections of the amphibolitic-gneissic country rock associated with the anorthosite body show the great compositional variations of the rocks in the study area. In all three cases the rocks are fine- to medium-grained showing granoblastic, polygonal textures.

One sample is a poorly-banded gneiss containing up to 55 percent plagioclase  $(An_{60})$  and about 20 percent each of coexisting augite and hyperstheme. The hyperstheme is strongly pleochroic from pale green to pink. The textures and the presence of pyroxenes is indicative of the granulite facies of regional metamorphism.

Another thin section is a hornblende-plagioclase gneiss. It contains up to 55 percent plagioclase  $(An_{54})$  and up to 15 percent chloritized hornblende. The hornblende forms irregular bands usually 2 millimetres in width. Biotite (up to 3 percent of total) and minor augite are commonly associated with the hornblende.

The last of these three thin sections is an amphibolite which forms a small lens in the anorthosite. It consists of bands of hornblende (up to 60 percent) and plagioclase. The chloritized hornblende has dark green to colorless pleochroism and usually has a small percentage of associated magnetite. The plagioclase has an anorthite content of around  $An_{54}$  and may have poorly developed epidote rims. Minor amounts of orthoclase are also present in the plagioclase bands. One thin section examined was taken from the mylonite zone southeast of the anorthosite body. The mylonitic-blastomylonitic texture of the rock is well developed and the matrix (up to 70 percent of total rock) is foliated, consisting of very fine-grained quartz, feldspar and muscovite. Oriented parallel to the foliation are porphyroblasts of plagioclase and quartz. They are usually anhedral and oval in shape with embayed rims. Some subhedral plagioclase porphyroblasts are also present. The porphyroblasts are up to 2 millimetres across and most twin lamellae in the plagioclase are fuzzy to invisible. There is some minor symplectic growth of quartz and feldspar in a few of the porphyroblasts.

#### CHAPTER 4 WHOLE ROCK GEOCHEMISTRY

#### Major Element Composition

An analysis of the major element composition for five samples, three anorthosites (PM-1-1, PM-2-3A, PM-2-6) and two country rocks (PM-2-4, PM-2-9), by the electron microprobe is presented in Table 1. The normative mineralogy for the anorthosite samples has also been calculated and is shown in Table 2.

The major element composition of each anorthosite is very similar and the relatively high  $Al_20_3$  content is due to the fact that the anorthosites are composed predominantly of plagioclase. The slightly higher FeO + Fe<sub>2</sub>O<sub>3</sub> and MgO contents of PM-2-6 over the other two anorthosites is probably a result of the presence of minor amounts of hornblende (< 5%) in that sample. All three samples are quartz-normative but modal quartz has only been found in PM-2-6 (< 1%). The modal quartz is probably secondary, possibly due to the metamorphic breakdown of ferromagnesian minerals. The normative quartz content of these samples is unusually high for anorthositic rocks and may be due to non-isochemical metamorphism in which silica was added to the anorthosite. Sample PM-2-6 also has more normative clinopyroxene and orthopyroxene, probably a reflection of the hornblende as well.

The country rock samples differ in chemistry from the anorthosites and from each other. Sample PM-2-4 is an amphibolite and the high CaO, MgO, FeO (includes  $Fe_2O_3$ ) and TiO<sub>2</sub> abundances reflect the presence of

ROCK TYPE	Anorthosite	Anorthosite	Anorthosite	Amphibolite	Mylonite
SAMPLE	PM-1-1	PM-2-3A	PM-2-6	РМ-2-4	РМ-2-9
si0 <sub>2</sub>	57.77	58.21	57.65	55.08	77.01
TiO <sub>2</sub>	0.14		0.26	1.31	
Al_0_3	25.72	25.84	23.88	13.46	12.52
*Fe2 <sup>0</sup> 3	0.08	0.12	0.35	1.2	0.16
Fe0	0.49	0.68	1.94	7.04	0.19
MnO				0.11	
MgO	0.21	0.15	1.30	8.21	0.12
Ca0	8.55	9.08	10.14	12.69	1.51
Na <sub>2</sub> 0	5.55	5.27	4.40	0.86	2.19
к <sub>2</sub> 0	0.83	0.74	0.26	0.14	4.02
SUM	99.34	100.09	100.18	100.00	98.42

$$* \frac{Fe_2^{0}}{Fe_2^{0} + Fe_3^{0}} = 0.15$$

Table 1. Major element chemistry of three anorthosite and two country rock samples from the study area.

NORMATIVE MINERALS	PM-1-1	рм-2-3а	PM-2-6
Q	3.42	4.60	7.31
OR	4.94	4.37	1.54
AB	47.27	44.55	37.16
AN	42.70	44.63	44.57
DI	0.00	.32	4.66
НҮ	1.13	1.36	3.77
MT	.12	.17	.51
IL	.27	0.00	.49
С	.15	0.00	0.00
TOTAL	100.00	100.00	100.00

Table 2. Normative mineralogy of the anorthosite samples. (Q = quartz; OR = orthoclase; AB = Albite; AN = anorthite; DI = diopside; Hy = hypersthene; MT = magnetite; IL = ilmenite; C = corundum) up to 60 percent hornblende and minor associated Fe-Ti oxides. The low Na<sub>2</sub>O values result from the calcic (labradorite) plagioclase in the amphibolite, as opposed to the more sodic plagioclase of the anorthositic rocks.

The other country rock sample PM-2-9, a mylonite, has up to 85 percent quartz in the modal mineral analysis. This percentage may be original, but processes such as silicification may have occurred during and/or after mylonitization and other major elements may have been mobilized and partly released from the system. The relatively high K<sub>2</sub>O content of this rock reflects the presence of minor orthoclase in the matrix.

### Rare Earth Element Analysis

Restrictive limits on possible parent magmas of anorthosites can be determined by using recent advances in the petrogenetic applications of rare earth elements (REE) (Simmons and Hanson, 1978). Such advances include higher quality analyses, quantitative approaches for describing the behaviour of REE during fractional crystallization and partial melting and a larger number of mineral-melt distribution coefficients ( $K_D$  's) (Simmons and Hanson, 1978). Rare earth elements are also particularly useful for such studies because they are a chemically coherent group (Simmons and Hanson, 1978) and are immobile during many geologic processes. Green <u>et al</u>. (1969, 1972) and Duchense and Demaiffe (1978), for example, have demonstrated the relative immobility of REE with increasing grades of metamorphism and in retrogressive metamorphic events (even when complete recrystallization occurs).

The rare earth element contents (La, Ce, Nd, Sm, Eu, Tb, Yb, Lu) of the same five samples (PM-1-1, PM-2-3A, PM-2-6, PM-2-4, PM-2-9) have been determined by neutron activation (Table 3) and are plotted in Figures 5,6. All values are relative to the average REE content of chondrites as determined by Haskin <u>et al</u>. (1968) (La 0.33 ppm; Ce 0.88 ppm; Nd 0.60 ppm; Sm 0.18 ppm; Eu 0.069 ppm; Tb 0.047 ppm; Yb 0.20 ppm; Lu 0.034 ppm) (Table 4).

The distribution of rare earths in anorthosites is controlled largely by the plagioclase of which they are mainly composed (Philpotts et al., 1966). The chondrite-normalized REE distribution patterns of the anorthosites (Fig. 5) are well-fractioned (especially PM-1-1, PM-2-3A) and show a marked depletion in the heavy REE. Sample PM-2-6 does not have, however, as much a depletion in the heavy REE as the other two. Patterns in all three are similar for the light REE except PM-2-3A which is somewhat more depleted in Sm. O'Nions and Pankhurst (1974) have expressed the degree of fractionation as the ratio of the chondrite-normalized Ce abundance to the chondrite-normalized Yb abundance  $(Ce_n/Yb_n)$ . The ratios for PM-1-1 and PM-2-3A are 19.4 and 26.8 respectively but for PM-2-6 the ratio is only 3.6 These values are generally higher than those for the anorthosites described by O'Nions and Pankhurst (1974) from the Godthab area of western Greenland but are much less than those obtained by Philpotts et al. (1966) for an anorthosite body in Quebec (Ce<sub>n</sub>/Yb<sub>n ~</sub> 45). The less fractionated pattern from

SAMPLE	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	ppm
PM-1-1	2.87	5.28	5.60	0.83	0.887	0.058	0.062	0.000	
PM-2-3A	3.19	5.29	3.11	0.35	0.805	0.062	0.045	0.000	
PM-2-6	2.98	5.47	3.12	0.73	0.706	0.148	0.346	0.103	
PM-2-4	4.48	8.82	24.25	5.99	0.962	0.439	1.883	0.325	
PM-2-9	10.87	17.95	10.46	1.96	1.958	0.201	0.677	0.149	

Table 3. REE content (ppm) of the Cape Breton anorthosite (PM-1-1, PM-2-3A, PM-2-6) and surrounding country rock (PM-2-4= amphibolite, PM-2-9 = mylonite).

SAMPLE	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	ppm
PM-1-1	8.71	6.00	9.34	4.60	12.855	1.234	0.31		
PM-2-3A	9.68	6.02	5.19	1.95	11.667	1.319	0.23		
PM-2-6		6.22						3.029	
PM-2-4	13.56	10.18	40.42	33.10	13.94	9.34	9.44	9.56	
PM-2-9	32.94	20.40	17.43	10.10	7.33	4.28	3.39	4.38	

Table 4. Chondrite-normalized values for the anorthosite and country rock samples.

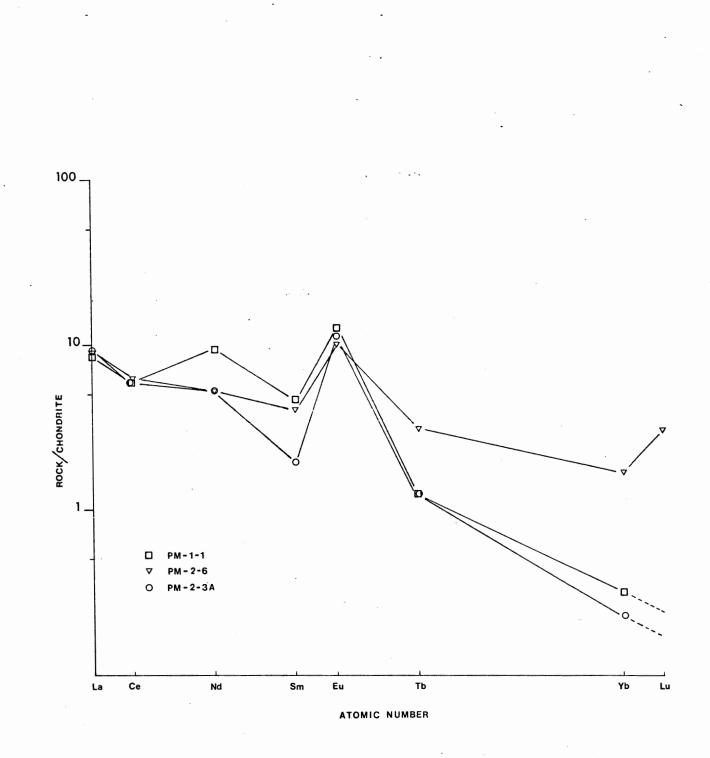
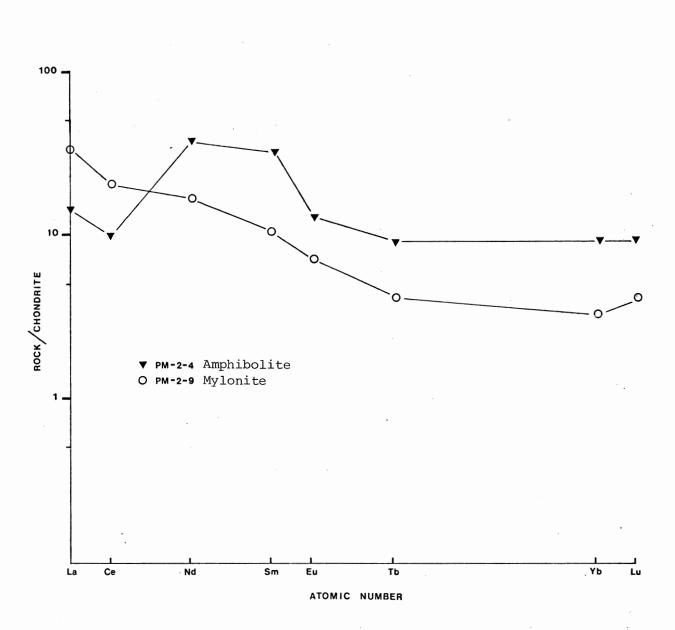
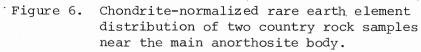


Figure 5. Chondrite-normalized rare earth element distribution of anorthosite samples.

- 25 -





- 26 -

PM-2-6 might be expected from a gabbroic anorthosite (Green <u>et al.</u>, 1972) and this sample does contain more Fe and Mg than the other two.

The REE content of the anorthosites is also very low in comparison to other rock types such as amphibolites, gneisses, and mangerites described by Green <u>et al.</u>, 1972, and all three samples have a marked positive Eu anomaly, especially PM-2-3A. The ratio Eu/Eu\* is 4.5, 6.4 and 3.8 for PM-1-1, PM-2-4 and PM-2-6, respectively. The positive anomaly is caused by the preference of plagioclase to accept  $Eu^{2+}$ , over trivalent  $Eu^{3+}$  and the other REE, because its similar valency and size to  $Ca^{2+}$  (Jakes and Taylor, 1974).

The REE patterns for the country rocks (PM-2-4 and PM-2-9) (Fig. 6) differ from the anorthosites as well as from one another. The mylonite (PM-2-9) exhibits a linear fractionated pattern ( $Ce_n/Yb_n = 6.02$ ) with a REE concentration 2-10 times higher than that of anorthosite. There is no evidence of an Eu anomaly (Eu/Eu\* = 1.0) and therefore the mylonite is probably not related to the parental magma from which the anorthosite was derived. A negative Eu anomaly would have been expected if the mylonite rocks were a late-stage differentiate from the magma which gave rise to the anorthosite.

The amphibolite (PM-2-4) has, in general, a non-fractionated pattern as the ratio  $Ce_n/Yb_n$  is only 1.08 and the Eu/Eu\* ratio is 0.6. Such data seem to preclude any direct relationship between the origin of the amphibolite and that of the anorthosite or mylonite rock. This sample has unusually high Nb and Sm values that do not fall into the linear trend of the other REE.

### CHAPTER 5 MINERAL CHEMISTRY

#### Determination of Plagioclase Compositions

The electron microprobe has been used to determine the composition of plagioclase grains from ten samples of the anorthosite and the country rock. At least six different plagioclase crystals from each thin section were examined in order to ascertain any variation within a single rock. The average analysis and subsequent anorthite-albiteorthoclase contents of the feldspars are given in Table 5. A ternary plot (An-Ab-Or system) of the composition of the plagioclases from the samples is shown in Figure 7. The plagioclase of the anorthosite has a compositional range from An<sub>34</sub> to An<sub>49</sub> and the country rock gneisses contain plagioclase ranging from An<sub>56</sub> to An<sub>61</sub>.

## Compositional Analysis of Coexisting Pyroxenes

The analysis of the composition of coexisting pyroxenes (orthopyroxene and clinopyroxene) from sample K15-0530 has been performed using the electron microprobe and, to insure a representative analysis, at least four different grains of each type of pyroxene were examined. Table 6 gives the compositional analysis for the average of each pyroxene type. A plot of the pyroxene compositions in the system Di-Hd-En-Fs is shown in Figure 8.

The compositions of coexisting Ca-rich (cpx) and Ca-poor (opx) pyroxenes have proven to be a useful tool for estimating the equili-

- 28 -

ROCK TYPE	Anortho- site	Anortho- site	Anortho- site	Anortho- site	Anortho- site	Anortho- site	Horn- blende Anortho- site	Anortho- site	Gneiss	Gneiss
	K15-0020	к15-0049	K15-0520	K15-0522	K15-0525	K15-0548	K15-0551	РМ-2-6	к15-0530	к15-0531
SiO <sub>2</sub>	60.19	57.35	56.52	56.69	56.43	58.16	58.96	65.45	53.30	54.54
Al <sub>2</sub> 0 <sub>3</sub> FeO (in- cludes Fe <sub>2</sub> O <sub>3</sub> )	25.30 0.15	26.46 0.14	27.38 0.14	27.66 0.14	27.13 0.05	26.34 0.05	25.81 0.00	27.59 0.14	29.43 0.19	0.10
Ca0	7.22	8.82	9.14	10.18	9.77	8.81	7.72	10.08	12.86	11.80
Na <sub>2</sub> 0	7.42	6.59	5.99	5.71	6.18	6.69	7.29	5.83	4.33	4.94
K20	0.19	0.23	0.21	0.20	0.11	0.24	0.08	0.12	0.24	0.22
SUM	100.47	99.59	99.38	99.58	99.67	100.29	99.86	100.21	100.35	100.29
Anorthite	34.6	42.0	45.2	49.1	46.4	41.6	36.7	48.5	61.3	56.2
Albite	64.3	56 <b>.7</b>	53.6	49.8	53.0	57.1	62.8	50.8	37.3	42.6
Orthoclase	1.1	1.3	1.2	1.1 ,	0.6	1.3	0.5	0.7	1.4	1.2

1

Table 5. Chemical analyses of feldspars from anorthosites and country rocks.

- 29 -

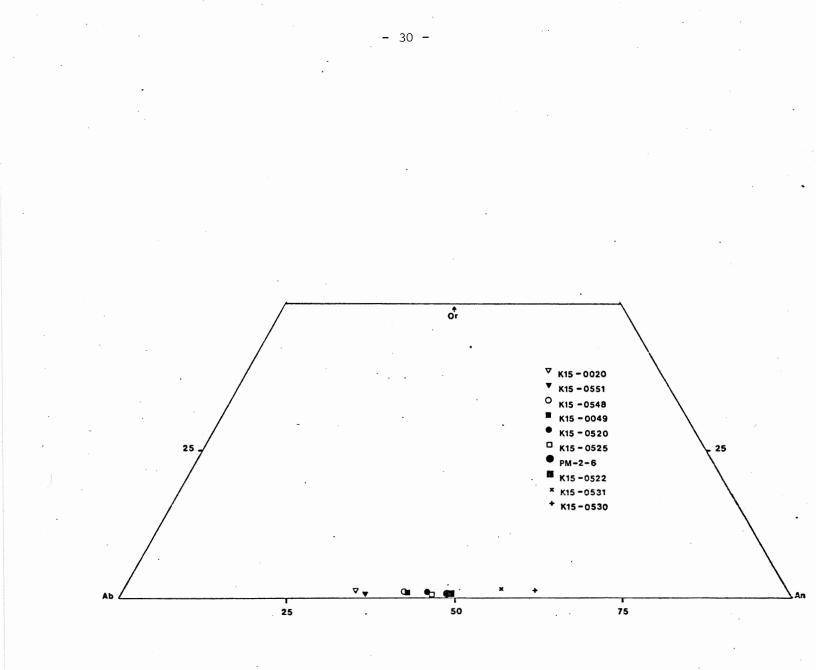


Figure 7. Plot of the An-Ab-Or content of ten samples from the study area, as determined by electron microprobe analysis.

SAMPLE K15-0530		Cpx		
SiO <sub>2</sub>		51.22		
Al <sub>3</sub> 0 <sub>3</sub>		2.04		
TiO2		0.23		
FeO (includes Fe <sub>2</sub> O <sub>3</sub> )		11.05		
MnO		0.22		
MgO		12.95		
Ca0		22.18		
SUM		99.89		
CATION	ORIGINAL	NORMALIZED	ORIGINAL	NORMALIZED
Si	1.956	1.950	1.934	1.927
Al <sup>3+</sup> tet	.044	0.044	0.66	0.660
Al <sup>3+</sup> oct	.018	0.018	0.25	0.250
Ti	0.000	0.000	.007	0.007
Fe <sup>3+</sup>	0.000	0.032	0.00	0.048
Fe <sup>2+</sup>	0.931	0.896	0.349	0.300
Mn	0.018	0.018	.007	0.007
Mg	1.020	1.017	0.729	0.726
Ca	0.025	0.025	0.897	0.894
SUM	4.013	4.000	4.014	4.000

Table 6. Pyroxene analysis from sample K15-0530.

~

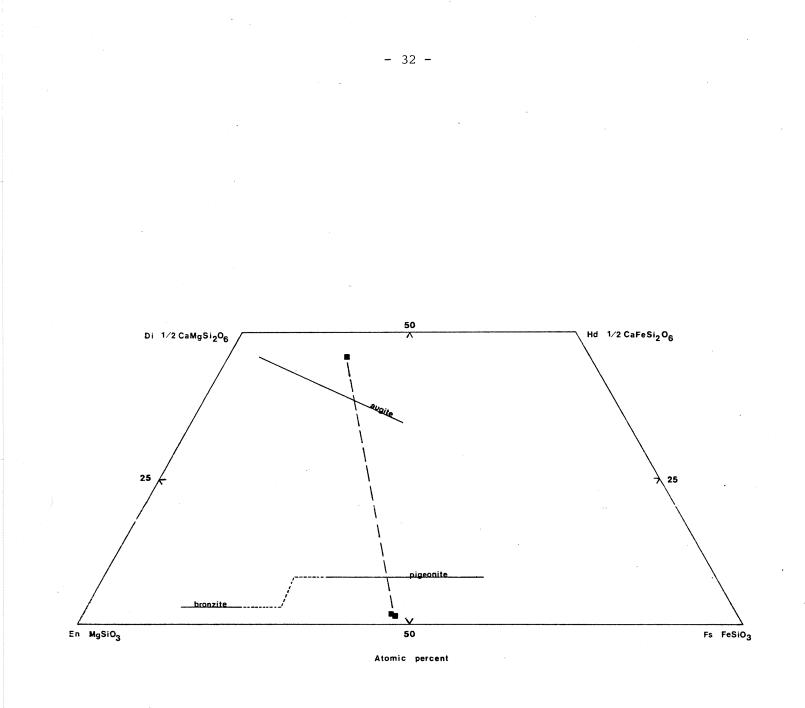


Figure 8. Plot of the compositions of the coexisting pyroxenes from sample K15-0530 in the lower portion of the  $CaSiO_3-MgSiO_3-FeSiO_3$  system. Phase boundaries adapted from Yang (1973), Ross *et al.* (1973) and Boyd and Brown (1969) for the Bushveld intrusion.

brium temperature at which they formed (Binns, 1962; Ross <u>et al</u>., 1973; Wood and Banno, 1973; Ross, 1975; Wells, 1977; Pride, 1978; Bohlen and Essen, 1978). The composition, however, must be expressed in terms of cation content (based on six oxygens) to be used in the geothermometer (Table 6) (Wood and Banno, 1973).

Since all iron is calculated as FeO in the microprobe analysis, only  $Fe^{2+}$  is given and a  $Fe^{3+}$  value must be calculated. In this case, the absence of Na<sup>2+</sup> rules out the possibility that  $Fe^{3+}$  has been taken up in an acmite [NaFe<sup>3+</sup> (Si<sub>2</sub>O<sub>6</sub>)] component and any Al<sup>3+</sup> (tetrahedral) will not have been used in a jadeite [NaAl (Si<sub>2</sub>O<sub>6</sub>)] component. This means that any  $Fe^{3+}$  and tetrahedral Al<sup>3+</sup> will probably be taken up in a Tschermak's molecule:

## (CaA13+) VI (A13+Si) IV06

where  $Fe^{3+}$  can substitute for  $Al^{3+}$  in either the tetrahedral or octahedral site. The sum of the octahedral and tetrahedral cations in such a Tschermak's molecule must equal four (based on six oxygens) such that the octahedral cations sum to two and the tetrahedral cations sum to two. If the ratio of cations to oxygen is not 4:6, then the ferrous iron can be converted to ferric iron by the reaction:

# $2\text{FeO} + \frac{1}{2}\text{O}_2 \rightarrow \text{Fe}_2\text{O}_3$

until the cation/anion ration reaches 4:6. The amount of iron converted in this reaction will be the theoretical value of  $Fe^{3+}$  which is used in the calculation of the equilibration temperatures in chapter 6.

- 33 -

#### CHAPTER 6 DISCUSSION

## Plagioclase Composition Variation

The variation in the anorthite content of the plagioclase throughout the anorthosite body ranges from  $An_{34}$  to  $An_{49}$ , ie, in the andesine range. There does not seem to be any direct relationship between the An content and the location of the sample in the anorthosite (Fig. 9) and two basic processes that might explain this heterogenous distribution are presented below.

In the first instance, the anorthosite may have originally been homogeneous in terms of plagioclase composition and any variation now present may be due to localized metamorphic events. Carmichael <u>et al</u>. (1974) note that metamorphic recrystallization of plagioclase will tend to give it a more sodic composition by the removal of calcium from the system. In this case the Ca released by the plagioclase may remain in the rock as epidote (chlorite) or may be completey removed.

In the second case, the variation may be a tectonic effect instead of a metamorphic effect. The anorthosite may have been heterogenous prior to emplacement with some sort of cryptic layering developed. During forceful emplacement of the anorthosite body, as suggested by Jenness (1966), this layering may have been sheared, resulting in the juxtaposition of different cryptic zones, each with a different plagioclase composition. Such a tectonic event may also explain the granulation of the plagioclase crystals in the anorthosite.

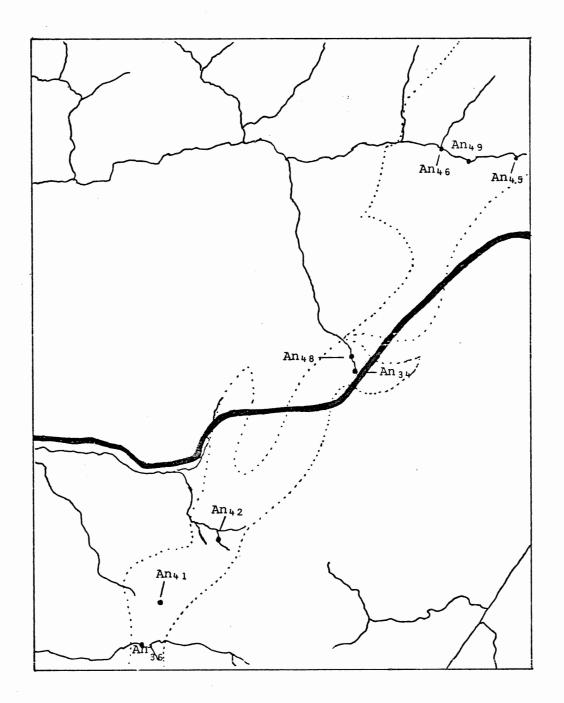


Figure 9. Variation of the plagioclase An content (as determined by electron microprobe analysis) in the main anorthosite body.

- 35 -

## Pyroxene Geothermometry

Sample K15-0530 is a two-pyroxene banded gneiss closely associated with the anorthosite. Coexisting pyroxenes (Ca-rich clinopyroxenes and Ca-poor orthopyroxenes) are, as mentioned, useful geothermometers of equilibration temperatures in igneous and metamorphic rocks because the distribution coefficients ,  $Ca/(Mg + Fe^{2+})$  and  $Fe^{2+}/Mg$ , between the pyroxenes are temperature sensitive (Bohlen and Essene, 1978). Kretz (1963) has demonstrated that the distribution coefficient  $(K_D)$  of the Mg and Fe<sup>2+</sup> distribution between coexisting pyroxenes phases differs in igneous and metamorphic rocks. The K<sub>D(Mg-Fe)</sub> varies with temperature, pressure and the concentration of other elements, such as Al, Fe<sup>3+</sup>, Ca and Ti, so it is more of an indication of the physico-chemical conditions under which the pyroxenes formed and not a true distinguishing factor between igneous and metamorphic assemblages (Atkins, 1969). The K<sub>D(Mq-Fe)</sub> for the coexisting pyroxenes of sample K15-0530 is 0.47. This  $K_D$  is well below the igneous field as defined by Kretz (1963) which ranges from 0.65 to 0.86 and is closer to his metamorphic field of 0.51 to 0.65 (Fig. 10). Thus, according to this approach, these pyroxenes seem to have formed in the lower ranges of the high-temperature metamorphic field.

Ross (1975) has developed a temperature-composition relationship for naturally occurring assemblages of coexisting pyroxenes in the ternary phase ( $CaSiO_3 - MgSiO_3 - FeSiO_3$ ) at pressures less than 5 kilobars. The plot of the pyroxenes from sample K15-0530 in such a diagram is

- 36 -

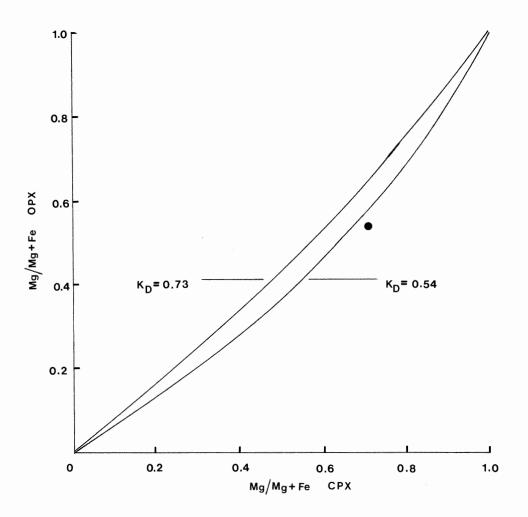


Figure 10. Plot of the  $K_{D(Mg-Fe)}$  between coexisting pyroxenes of metamorphic ( $K_{D} = 0.54$ ) and igneous ( $K_{D} = 0.73$ ) rocks (adapted from Kretz, 1963).

• =  $K_{D(Mg-Fe)}$  of sample K15-0530 coexisting pryoxenes.

shown in Figure 11. These coexisting pyroxenes are an equilibrium assemblage since the tie line between them is nearly parallel to tie lines estimated by Ross (1975) for other equilibrated pyroxene pairs. The estimated equilibration temperature is about 700°C, in the mid-range of the granulite facies of regional metamorphism.

Wood and Banno (1973) base a pyroxene geothermometer on the solubility of enstatite in clinopyroxene coexisting with orthopyroxene. The reaction of interest in this case is:

(Mg<sub>2</sub>Si<sub>2</sub>0<sub>6</sub>)<sub>opx</sub> (Mg<sub>2</sub>Si<sub>2</sub>0<sub>6</sub>)<sub>cpx</sub> enstatite-diopside solid solution diopside-enstatite solid solution The effect of pressure on this reaction may be neglected since a pressure increase from 1 bar to 30 kilobars will result in a difference in equilibration temperature of only 50C° (or less) (Wood and Banno, 1973; Wells, 1977). The temperature relationship they have determined is shown in equation (1) below:

$$T(^{\circ}K) = \frac{-10202}{(1)}$$

$$\ln \frac{a_{Mg_{2}Si_{2}0_{6}}^{Cpx}}{a_{Mg_{2}Si_{2}0_{0}}^{Opx}} - 7.65 X_{Fe}^{Opx} + 3.88 (X_{Fe}^{Opx})^{2} - 4.6$$

$$Where \frac{a_{Mg_{2}Si_{2}0_{6}}^{Cpx}}{Mg_{2}Si_{2}0_{6}} = \frac{Mg^{2+}}{Mg^{2+}+Fe^{2+}+Ca^{2+}+Mn^{2+}+Na^{2+}} \times \frac{Mg^{2+}}{Fe^{2+}+Mg^{2+}+Fe^{3+}+A1^{3+}}$$
in clinopyroxene  

$$a_{Mg_{2}Si_{0}6}^{Opx} = above, in orthopyroxene$$

$$\frac{X_{Fe}^{Opx}}{Fe} = \frac{Fe^{2+}}{Fe^{2+}+Mg^{2+}} \text{ orthopyroxene}$$
(1)

They have concluded that this approach is accurate to + 60°C within a

- 38 -

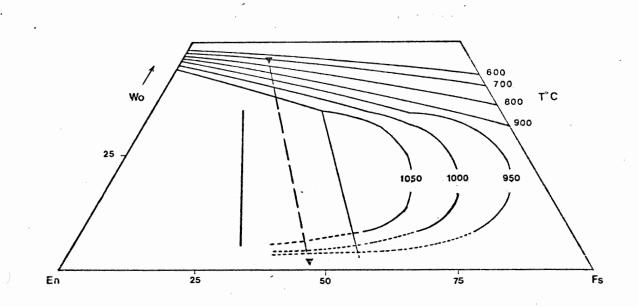


Figure ll.

Temperature - (CaSi0<sub>3</sub> - MgSi0<sub>3</sub> - FeSi0<sub>3</sub>) diagram for naturally occurring pyroxene assemblages at pressures less than 5 kilobars; solid lines cross-cutting the isotherms are tie lines between stable coexisting pyroxenes (Ross, 1975). ▼ = coexisting pyroxene compositions from sample K15-0530. temperature range of 700°-1400°C. Hewins (1975) notes that this approach is very useful as a geothermometer because of its internally consistent, precise and apparently accurate temperature determinations. The temperature calculated for the sample K15-0530 is 870°C, a temperature consistent with the granulite facies.

Wells (1977) has used the above equation (1) and has recalibrated it using more recent data and has developed a slightly different equation (2) to determine the equilibration temperatures:

$$T (^{O}K) = \frac{7341}{3.355 + 2.44 X_{F_{\Theta}}^{OPX} - \ln K}$$
(2)

where

$$\frac{\text{Fe}^{2+}}{\text{Fe}^{2+} + Mq^{2+}} \text{ orthopyroxend}$$

$$K = \frac{a_{Mg_2Si_20_6}^{cpx}}{a_{Mg_2Si_20_6}^{opx}}$$

His equation is accurate to <u>+</u> 70C° in the temperature range 785°C-1500°C and is allegedly more reliable in Mg-rich coexisting pyroxenes. The Wells approach and the Wood-Banno approach deviate noticeably in low temperature ranges. The temperature estimate for sample K15-0530 by the Wells geothermometer is 932°C, also consistent with the granulite facies.

Hewins (1975) subdivides the granulite facies into two subfacies: a) the hornblende-granulite subfacies where rocks crystallized in the range 760°C-860°C and b) the pyroxene-granulite subfacies where rocks crystallized at temperatures greater than 860°C. The estimated equilibration temperatures are thus indicative of the pyroxene-granulite subfacies.

The rough estimate of pressure can be made assuming the equilibration temperature is in the range 870-930°C by using Ross (1975). His method, as mentioned, gives an estimated temperature of 700°C for these coexisting pyroxenes, but this is only valid for pressures less than 5 kilobars. Higher temperatures (such as 870°-930°C) will be found at higher pressures in his model, so it seems that the coexisting pyroxenes from sample K15-0530 may have formed at pressures greater than 5 kilobars.

In summary, the coexisting Ca-rich and Ca-poor pyroxenes of sample K15-0530 (a banded gneiss closely associated with the anorthosite) equilibrated at a temperature between 870°C and 932°C in the pyroxene-granulite subfacies and at a pressure probably higher than 5 kilobars.

#### REE Modelling of the Anorthosite Parent Magma

The nature of the parent magma for massif-type anorthosites is a controversial subject, as previously stated, and various compositions, ranging from gabbroic to granodioritic, have been suggested. Most estimates of the original parental magma composition are based on the volume proportions of the rocks associated with the anorthosite. Disagreement on the exact nature of this association, i.e., if the country rocks are derived from the same magma as the anorthosite, has resulted in considerably different proportions (Duchense et al., 1974) and thus the wide compositional range for the parental magma. Green (1969) has conducted high-pressure experiments to determine a compositional range for anorthosite parent magmas. He has concluded that anorthosites are products of fractionation from, or partial melting of, andesitic (quartzdioritic), deep-seated crustal material. Simmons and Hanson (1978), on the basis of whole rock chemistry, have suggested that the parent magma for anorthosites is a result of partial melting of deep-seated tholeiitic material.

A procedure to model the REE content of the parent magma, or the residual liquid if extensive fractionation has occurred in this parent magma, of the Cape Breton anorthosite is presented below. Several assumptions, however, must be made to utilize this model. These are as follows: a) the normative mineralogy of the anorthosite (Table 2) must be an accurate assessment of the original mineralogy, i.e., the bulk chemistry must have remained unchanged after metamorphism; b) the average normative mineralogy of the anorthosites PM-1-1 and PM-2-3A is representative of the mineralogy of the average anorthosite in the study area (PM-2-6 is not included here because the high normative quartz content seems to indicate that some alteration has occurred in this sample); c) the normative quartz and Fe-Ti oxides take up no appreciable amount of REE; d) the mineral/liquid distribution coefficients ( $K_D$ 's) for andesitic compositions (Table 7) must be applicable; e) the concentration of REE in the parent magma ( $C_P$ ) is given as:

- 42 -

к <sub>D</sub>	Ce	Nđ	Sm	Eu	Ÿb	Lu
Plagioclase	.202	.140	.107	.732	.033	.034
Орх	.038	.058	.100	.079	.671	.838
Срх	.508	.645	.954	.681	1.30	1.28
Orthoclase	.044	.025	.018	1.13	.012	.015*

\*By extrapolation

Table 7. REE partition coefficients (K 's) (Plagioclase, Opx, Cpx for andesite; orthoclase for rhyodacite) (adapted from Schnetzler and Philpotts, 1970).

$$D_0 = \frac{C_A}{C_P}$$

where  $C_A$  = concentration of a REE in the anorthosite  $C_P$  = concentration of a REE in the parent magma  $D_0$  = bulk distribution coefficient  $(D_0 = \Sigma_i^n X^i K_D^i; X^i = weight fraction of mineral$   $K_D^i = mineral/melt distribution coefficient of$ mineral i)

if the anorthosite represents an infinitesimally small proportion of the crystal-liquid system; and (f) if it is an adcumulate, ie., no interstitial fluids existed in the cumulate which would have enriched the whole rock in REE that would not be accounted for in D<sub>0</sub>.

Since it is highly probable that one or more of these assumptions is untenable, the modelling procedure is done mainly as an exercise to get a rough idea of the liquids coexisting with the anorthosites.

The following equation is used in this model to estimate the REE concentration in a residual liquid after the anorthosite fractionated from the parent magma:

$$C_{L} = \frac{C_{P}}{F_{l} + (F_{a}K_{Da}) + (F_{b}K_{Db}) + \dots + (F_{n}K_{Dn})}$$

where  $C_L$  = concentration of a REE in the residual liquid  $F_{\ell}$  +  $F_a$  +  $F_b$  + ...  $F_n$  = 1.00 (mass fractions of the liquid + crystal phases)

(a, b, ..., n are the various crystal phases)

The concentration of the REE in the liquid  $C_L$  has been determined for a liquid fraction ( $F_{\ell}$ ) from 1.00 ( $C_L = C_P$ ) to 0.50 in order to embrace the probable concentration range for the liquid that was in equilibrium with the Cape Breton anorthosite. The results of the above calculations for the parent and residual liquid are shown in Figure 12.

The REE content of the parent magma has a slightly fractionated trend  $(Ce_N/Yb_N = 4.96)$ , but only the heavy REE are fractionated. The light REE have an overall unfractionated trend. The parent magma is enriched in REE relative to the anorthosite and has an Eu/Eu\* ratio of 0.6. The residual liquid that would be in equilibrium with an anorthosite adcumlate that has been formed by 50 percent fractionation from the calculated parent has a pattern parallel to that of the parent magma. The pattern is, however, enriched in REE relative to the parent, as would be expected since the anorthosites take up relatively small amounts of REE, except for Eu. The fact that Eu is taken up in the plagioclases of the anorthosite is shown by the Eu/Eu\* ratio, equal to 0.4 in the residual liquid, which is slightly lower than in the parent magma.

The negative Eu anomaly (Eu/Eu\* = 0.6) of the calculated parent magma may be caused by several factors. The magma may already be a fractionated liquid derived from another source. The adcumulus assumption may be incorrect so that if the anorthosite was a cumulate, the REEenriched interstitial fluid would have to be taken into account. Failure to due so would give incorrect values for the REE content of the calculated parent magma. The bulk distribution coefficients may be

- 45 -

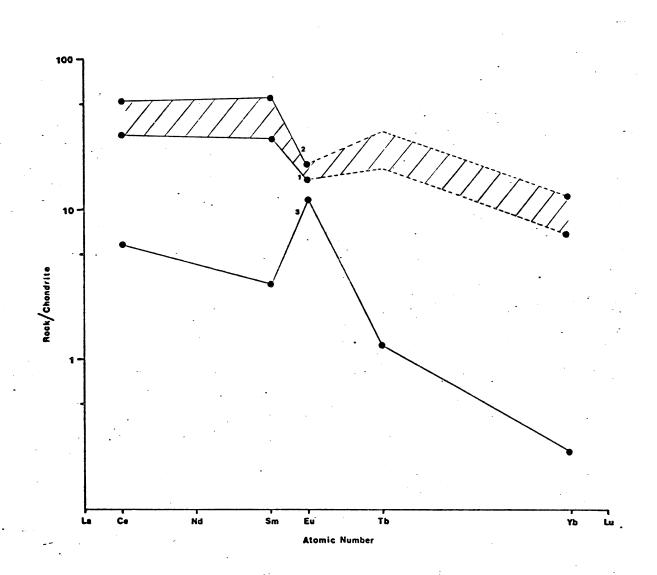




Figure 12. REE chondrite-normalized patterns for the parent magma of the anorthosite (1), a liquid in equilibrium with the anorthosite after 50 percent fractionation of crystal phases (2) and the average of samples PM-1-1 and PM-2-3A (3).

46 -

wrong due to inaccurate estimation of original mineral proportions or metamorphic effects on the mineralogy of the anorthosite. Finally, the  $K_{\rm D}$  values used may be inappropriate for the parent magma of this anorthosite.

A visual comparison of the REE chondrite-normalized pattern of the anorthosite parent magma to those of andesites, tholeiites and alkali basalts (Fig. 13-14) is made in an attempt to determine the nature of the parent magma. The patterns of andesites and alkali basalts are, on the whole, more fractionated (especially in the light REE) than that of the calculated parent magma. The tholeiites, on the other hand, have patterns of fractionation similar to that of the parent magma; i.e., they have relatively unfractionated light REE and slightly fractionated heavy REE patterns. An average Archean tholeiite from the Precambrian greenstone belts of the Canadian Shield (Condie and Baragar, 1974) has a pattern nearly parallel to that estimated for the anorthosite parent magma but a lower total REE abundance.

In summary, the REE content of the parent magma is enriched relative to the anorthosite and is slightly fractionated with a small, negative Eu anomaly. The pattern is very similar to that of tholeiitic rocks and thus the anorthosites may represent products of fractionation from a tholeiitic melt.

- 47 -

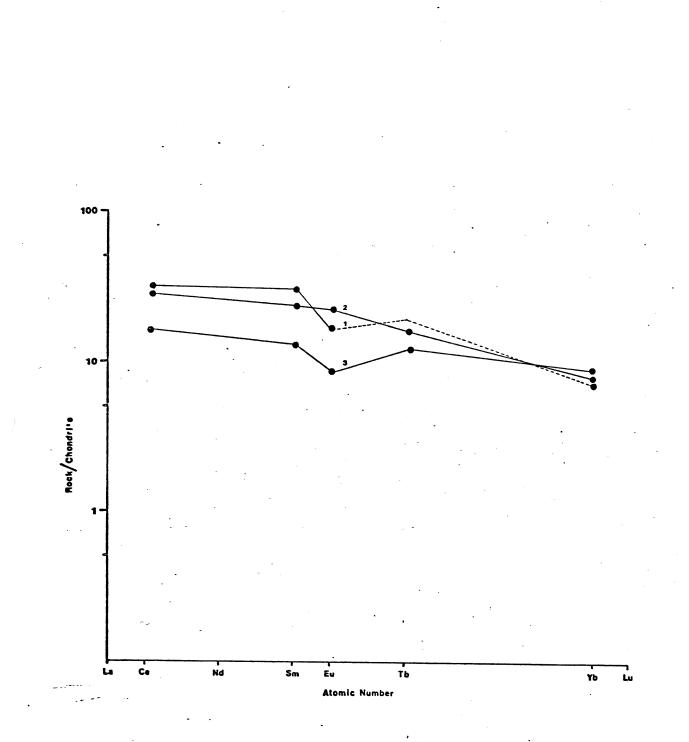
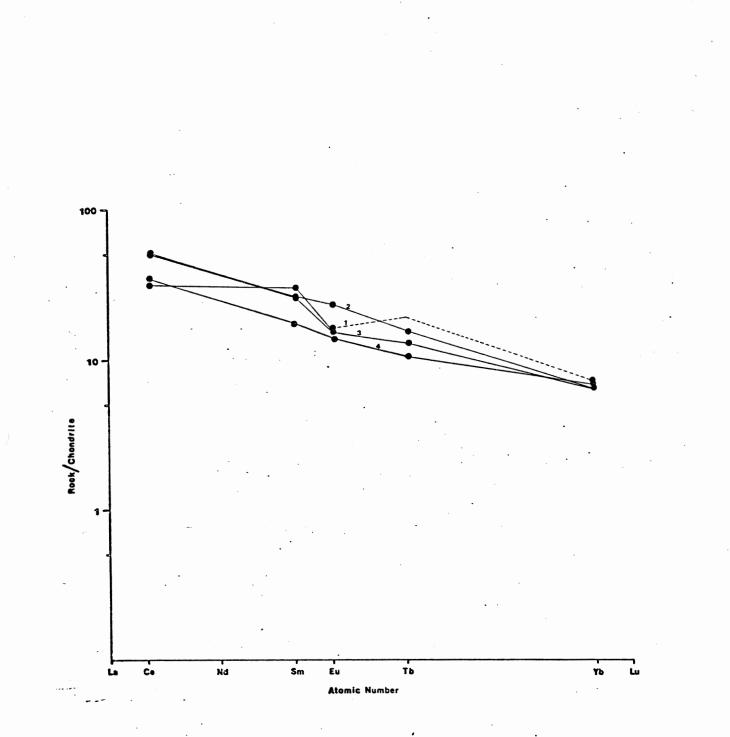
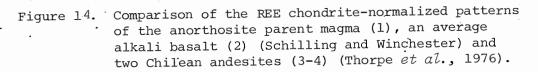


Figure 13.

Comparison of the REE chondrite-normalized patterns of the anorthosite parent magma (1), the average tholeiite (2) (Schilling and Winchester, 1969) and the average of 4 Archean tholeiites (3) (Condie and Baragar, 1974).

- 48 -





- 49 -

### REE Contents of Country Rock Samples PM-2-4 and PM2-9

The country rock samples, PM-2-4 (amphibolite) and PM-2-9 (mylonite) have, as mentioned, REE patterns that differ from the anorthosites as well as from one another. Both samples are enriched in REE as compared to anorthosites and do not seem to have been derived from the same source as the anorthosites. The patterns of each sample are compared to those of tholeiites and andesites (Figs. 15-16) in an attempt to determine possible origins.

The amphibolite (PM-2-4) has a relatively unfractionated trend with an unusually high Sm value (Fig. 15) (the Nd results have been omitted because of the large error in its determination). The trends for andesites and the average tholeiite are different from PM-2-4, exhibiting much higher Ce values and a more fractionated (especially heavy REE) trend. A sample of an Archean tholeiite from the Canadian Shield (Condie and Baragar, 1974) (Fig. 15), different from that compared to the parent magma (Fig. 13), has a pattern almost parallel to the pattern of the amphibolite. The marked depletion in light REE, and the low total REE abundance in the sample, are characteristic of mid-oceanic tholeiites (Jakes and Gill, 1970). The REE pattern is, however, significantly different from that estimated for the anorthosite parent magma so as to preclude any obvious relationship between the two, even though both apparently are derived from rocks of a tholeiitic composition.

The REE pattern of the mylonite (PM-2-9) is much more fractionated than that of either the amphibolite or the anorthosite parent magma.

- 50 -

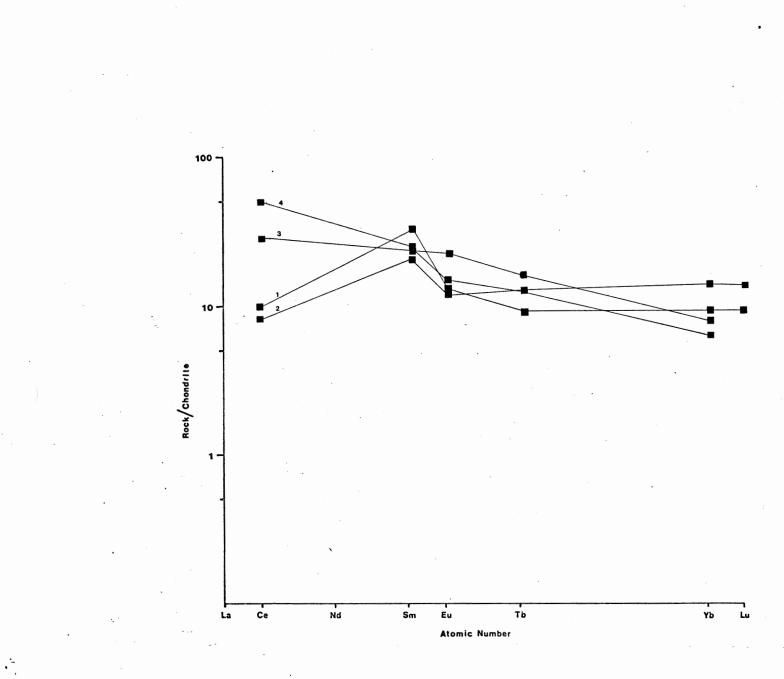
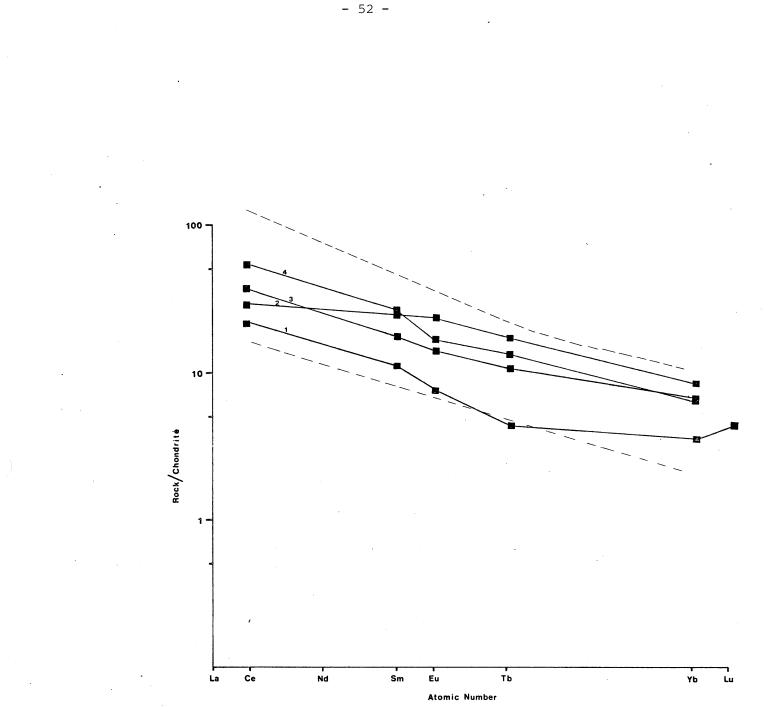


Figure 15.

Comparison of the REE chondrite-normalized pattern of the amphibolite PM-2-4 (1) to the patterns of an Archean tholeiite (2) (Condie and Baragar, 1974), the average tholeiite (3) (Schilling and Winchester, 1969) and a Chilean andesite (4) (Thorpe *et al.*, 1976).





REE pattern for the mylonite (PM-2-6) (1), the average tholeiite (2) (Schilling and Winchester, 1969) and two Chilean andesites (3 - 4) (Thorpe  $et \ all$ , 1976). Dashed lines represent the calc-alkaline, shoshonite and alkali rock field of island arcs (Jakes and Gill, 1970).

The average tholeiite has a similar pattern in the heavy REE but a much flatter light REE pattern. The mylonite pattern is, however, parallel to that of andesites (Fig. 16), and falls within the field estimated by Jakes and Gill (1970) for calc-alkaline, shoshonitic and alkaline rocks of island arcs (Fig. 16). The total REE abundances of the mylonite are generally low as compared to the andesites and may be more closely related to those developed by the shoshonites and alkali rocks from island arc environments.

To summarize, the amphibolite (PM-2-4) was probably formed from rocks similar in composition to mid-oceanic tholeiites and is not directly related to the tholeiitic anorthosite parent magma. The mylonite (PM-2-9), on the other hand, originally appears to have had a composition similar to that of island arc volcanics such as shoshonites and other related alkali rocks or andesites.

### Origin of the Anorthosite

The anorthosite, and the closely associated granulite gneisses, are situated in an area that has apprently only been metamorphosed to greenshist and amphibolite facies (Jenness, 1966). The pyroxene geothermometry from the gneisses are indicative of temperatures higher than 870°C, well above the amphibolite range, and pressures probably greater than 5 kilobars. Features in the anorthosite, such as granulation of plagioclase grains, the irregular compositional variation of the plagioclase and fault contacts with the country rock, and the associated mylonite zone are indicative of tectonic emplacement. The nearby Aspy Fault may also have been involved with the tectonic event leading to the emplacement of the anorthosite, but any exact relationship cannot presently be determined. The above factors indicate that the anorthosite and associated granulite gneiss were formed at depths and temperatures greater than the country rock in which they are now found and were forcefully emplaced into that country rock. The amphibolite lens (PM-2-4) found in the anorthosite may represent a piece of country rock that was incorporated in the anorthosite as it forced its way upward.

## CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

This thesis has examined the REE chemistry of the anorthosite and some associated country rock near Pleasant Bay, Cape Breton Island in an attempt to determine the nature of the anorthosite parent magma. The anorthosite plagioclases have also been studied with the use of the electron microprobe to determine any variation of their chemistry. Coexisting pyroxenes from a gneiss closely associated with the anorthosite have been used as a geothermometer to estimate metamorphic temperatures in this area.

The following is a list of conclusions from the above studies: (1) The anorthosite (massif- andesine -type) has a relatively low REE content (< 10 times chondrites) with a fractionated chondritenormalized REE pattern and a large, positive Eu anomaly.

(2) The anorthosite parent magma is enriched in REE relative to the anorthosite (< 35 times chondrites) with a fractionated chondritenormalized REE pattern and a small, negative Eu anomaly.

(3) The anorthosite parent magma probably had a tholeiitic composition.

- (4) The country rocks analysed for REE, an amphibolite and a mylonite, are not related to the anorthosite parent magma. The amphibolite probably originally had a tholeiitic composition and the mylonite may originally have had an andesitic composition.
- (5) There is an irregular variation of the An content of the plagioclase in the anorthosite that may be attributable to shearing during emplacement or to localized metamorphic events.

- (6) The coexisting pyroxenes of the gneiss associated with the anorthosite appear to have equilibrated at a temperature between 870°C – 932°C, indicative of the pyroxene-granulite subfacies of regional metamorphism, and probably at pressures greater than 5 kilobars.
- (7) Cataclastic textures in the anorthosites, an associated mylonite zone and high temperatures and pressures indicated by the associated granulite gneisses seem to indicate that the anorthosite has been tectonically emplaced from depth into rocks of the greenschist to amphibolite metamorphic facies.

This is only a preliminary study of the geochemistry of the Cape Breton anorthosites and to determine the origin of these bodies more accurately, more detailed work must be performed. An examination of the REE content of the entire anorthosite body will be useful to obtain a more reasonable picture of the variation across the body and aid in more accurate interpretations of the origin of the anorthosites and their relationship to surrounding country rock. Also, analysis for major elements, plus Rb, Sr, Ba must be presented to determine the chemical limits on the anorthosite parent magma. An examination of the <sup>87</sup>Sr/<sup>86</sup>Sr may help define a crustal or mantle origin for the anorthosite, as might a study of the oxygen and hydrogen isotopes. The REE content of the gneisses should also be studied since these rocks seem to have a close relationship to the anorthosite, and may aid in determining the composition of the anorthosite magma.

- 56 -

#### ACKNOWLEDGEMENTS

I would like to express my deepest appreciation to Dr. D. B. Clarke for without his help and invaluable criticism I would not have been able to complete this manuscript. I also appreciate his assistance, and that of Stephen Delahay, in completing my field work, even though weather conditions were not the best. I would also like to thank Dr. J. D. Keppie and P. Smith of the Nova Scotia Department of Mines who allowed me to use their samples and maps of the study area. The assistance of R. MacKay with the electron microprobe and Dr. Jagam in the neutron activation lab is also appreciated. Finally I would like to thank Carol Mitchell and Linda LeBlanc who were both instrumental in typing the first and/or final drafts of this manuscript.

- 57 -

#### REFERENCES

- Anderson, A.T. and Morin, M. (1966): Two types of massif-anorthosites and their implications regarding the thermal history of the crust. IN: Origin of anorthosites and related rocks. N.Y. State Museum and Science Service Memoir 18 (ed. Y.W. Isachen).
- Atkins, F.R. (1969): Pyroxenes of the Bushveld Intrusion, South Africa. J. Petrol. 10,222-249.
- Binns, R.A. (1962): Metamorphic pyroxenes from the Broken Hill district, New South Wales. Min. Mag. 33,320-338.
- Bohlen, S.R. and Essene, E.J. (1978): Igneous pyroxenes from metamorphosed anorthosite massifs. Cont. Min. Pet. 65,433-442.
- Boyd, F.R. and Brown, G.M. (1969): Electron-probe study of pyroxene exsolution. Mineral. Soc. Am. Spec. Pap. 2,211-216.
- Buddington, A.F. (1939): Adirondack igneous rocks and their metamorphism. Geol. Soc. Am. Memoir 7.
- Carmichael, I.S.E., Turner, F.J., Verhoogen, J. (1974): Igneous Petrology. McGraw-Hill Brook Co..
- Condie, K.C. and Baragar, W.R.A. (1974): Rare earth element distributions in volcanic rocks from Archean greenstone belts. Cont. Min. Pet. 45,237-246.
- deWaard, D. (1966): The anorthosite problem: The problem of the anorthosite-charnockite suite of rocks. IN: Origin of anorthosites and related rocks. N.Y. State Museum and Science Service Memoir 18 (ed. Y.W. Isachsen).

Duchense, J.C., Roelandts, I., Demaiffe, D., Hertogen, J., Gijbels, R., and DeWinter, J. (1974): Rare earth data on monzonoritic rocks related

to anorthosites and their bearing on the nature of the parental magma of the anorthosites series. Earth Plan. Sci. Letters 24,325-335.

Duchense, J.C. and Demaiffe, D. (1978): Trace elements and anorthosite genesis. Earth Plan. Sci. Letters 38,249-272.

Emslie, R.F. (1968): The geology of the Michikamau Intrusion, Labrador. Geol. Surv. Can. Paper 68-57.

Gordon, G.E., Randle, R., Goles, G.G., Corliss, J.B., Beeson, M.H. and Oxley, S.S. (1968): Instrumental activation analysis of standard rocks with high resolution X-ray detectors. Geochim. Cosmochim. Acta 32, 369-396.

Flanagan, F.J. (1972): 1972 values for international geochemical reference samples. Geochim. Cosmochim. Acta 37,1189-1200.

Green, T.H. (1969): High-pressure experimental studies on the origin of anorthosite. Can. J. Earth Sci. 6,427-440.

- Green, T.H., Brunfelt, A.O. and Heier, K.S. (1972): Rare earth element distribution and K/Rb ratios in granulites, mangerites and anorthosites, Lofoten-Vestevaalen, Norway, Geochim. Cosmochim. Acta 36, 241-257.
- Haskin, L.A., Wildeman, T.R., Haskin, M.A. (1968): An accurate procedure for the determination of the rare earths by neutron activation. J. Radanal. Chem. 1,337-348.

- 59 -

Hewins, R.H. (1975): Pyroxene geothermometry of some granulite facies rocks. Cont. Min. Pet. 50,205-209.

- Isachsen, Y.W. (1966): Origin of anorthosites and related rocks a summarization. IN: Origin of anorthosite and related rocks. N.Y. State Museum and Science Service Memoir 18 (ed. Y.W. Isachsen).
- Isherwood, F.B. (1974): Cape Breton Anorthosite. B.Sc. (Hon.) Thesis, Dalhousie University, Halifax, Nova Scotia.
- Jakes, P. and Gill, J. (1970): Rare earth elements and the island-arc tholeiitic series. Earth Plan. Sci. Letters 9,17-28.
- Jakes, P. and Taylor, S.R. (1974): Excess Eu content in Precambrian sedimentary rocks and continental evolution. Geochim. Cosmochim. Acta 38,739-745.
- Jenness, S.E. (1966): The anorthosite of northern Cape Breton Island, Nova Scotia; A petrological enigma. Geol. Surv. Can. Paper 66-21.
- Kretz, R. (1963): Distribution of magnesium and iron between orthopyroxene and calcic pyroxene in natural mineral assemblages. J. Geology 71,773-785.
- Neale, E.R.W. (1956): Pleasant Bay, Inverness and Victoria counties, Nova Scotia. Geol. Surv. Can. Prel. Map 55-24.
- Neale, E.R.W. (1964): Geology, Pleasant Bay, Cape Breton Island, Nova Scotia. Geol. Surv. Can. Map 1119A.
- O'Nions, R.K. and Pankhurst, R.J. (1974): Rare earth element distribution in Archean gneisses and anorthosites, Godthab area, west Greenland. Earth Plan. Sci. Letters 22,328-338.
- Philpotts, J.A., Schnetzler, C.C., Thomas, H.H. (1966): Rare earth abundances in an anorthosite and a mangerite. Nature 212,805-806.

- Pride, C. (1978): Rare earth element studies of a granulite facies terrain: The Lewiston of N.W. Scotland. Ph.D. Thesis, Dalhousie University, Halifax, Nova Scotia.
- Ross, M., Huebner, J.S., Dowty, E. (1973): Delineation of the one atmosphere augite-pigeonite miscibility gap for pyroxenes from lunar basalt 12021. Am. Mineral. 58,619-635.
- Ross, M., and Huebner, S. (1975): A pyroxene geothermometer based on composition-temperature relationships of naturally occurring orthopyroxene, pigeonite and augite. Internat. Conf. Geoth. Geobar., Extended Abstracts, Penn. St. Univ.
- Schilling, J-G. and Winchester, J.W. (1969): Rare earth contribution to the origin of Hawaiian lavas. Cont. Min. Pet. 23,27-37.
- Schnetzler, C.C. and Philpotts, J.A. (1970): Partition coefficients of rare earth elements between igneous matrix material and rock-forming mineral phenocrysts - II. Geochim. Cosmochim. Acta 34,331-340.
- Simmons, E.C. and Hanson, G.N. (1978): Geochemistry and the origin of massif-type anorthosites. Cont. Min. Pet. 66,119-135.
- Thorpe, R.S., Potts, P.J. and Francis, P.W. (1976): Rare earth data and petrogenesis of andesite from the North Chilean Andes. Cont. Min. Pet. 54,65-78.
- Wells, P.R.A. (1977): Pyroxene geothermometry on simple and complex systems. Cont. Min. Pet. 62,129-139.
- Werner, A.G. (1780): Axel von Kronstedts Versuch einer Mineralogie. Reported in: Origin of anorthosites and related rocks. N.Y. State Museum and Science Service, Memoir 18 (ed. Y.W. Isachsen).

Wood, B.J. and Banno, S. (1973): Garnet-orthopyroxene and orthopyroxene-clinopyroxene relationships in simple and complex systems. Cont. Min. Pet. 42,109-124.

Yang, H. (1973): Crystallization of iron-free pigeonite in the system anorthite-diopside-enstatite-silica at atmospheric pressure. Am. J. Sci. 273,488-497. A) Anorthosite

K15-0520 Anorthosite

Major Mineralogy:

Plagioclase:	- An <sub>38</sub> , 90-95% of total mineral content,
	- subhedral, medium-grained ( $\circ$ 1.5 mm) crystals,
	- relatively undeformed, minor granulation,
	- moderately sericitized.

Accessory Mineralogy:

Chlorite:	- <5% of total mineral content,
	- subhedral, elongate, lath-shaped crystals,
	usually <0.5 mm long,
	- occur at boundaries between plagioclase crystals.
Epidote, Clinozoisite:	- 1-2% of total mineral content,
	- anhedral crystals, usually <0.5 mm grain size,
	- alteration of plagioclase.
Apatite:	- <0.5% of total mineral content,
	- poikilitically enclosed in plagioclase, very
	fine-grained.
Textures:	- Medium-grained (average grain size $1.5$ mm) with a
	hypidiomorphic granular (equigranular) texture.
	Finer-grained secondary minerals found around the
	grain boundaries of the plagioclases. No major
	cataclastic textures, all plagioclase grains are
	randomly oriented.

Plate: I

K15-0522 Anorthosite

Primary Mineralogy:

Plagioclase:	- $An_{45}$ , 85% of total mineral content,
	- subhedral, medium-grained ( $01.5 - 2$ mm) crystals,
	often with poikilitic inclusions of accessory
	minerals such as sericite, epidote,
	- bent and granulated crystals common.

Accessory Mineralogy:

Epidote, Clinozoisite:	- 7% of total mineral content,
	- form individual, anhedral grains (∿l mm grain size)
	and minor, thin (<1 mm thick) veins,
	- alteration product of the plagioclase.
Chlorite:	- 5% of total mineral content,
	- fine-grained, often bent and folded laths,
	- minor associated muscovite.
Opaques:	- <1% of total mineral content,
	- associated with chlorite.
Textures:	- Medium-grained (average grain size ${\sim}2$ mm) with a
	hypidiomorphic to allotriomorphic granular texture.
	Plagioclase crystals are randomly oriented and cata-
	clastic textures, such as bent and shattered crystals,
	irregular grain boundary contacts and granulation,
	are common.

Plate: II

K15-0548, K15-0049 Anorthosite

Major Mineralogy:

Plagioclase:	- $An_{40}$ , 95% of total mineral content,
	- subhedral, medium-grained (1-3 mm),
	- granulated crystals, undulose extinction,
	- extreme sericitization,
	- poikilitic inclusions (epidote) are numerous.
Accessory Mineralo	дў:
Epidote:	- <2% of total mineral content,
	- anhedral grains, usually 0.5 mm grain size,
	- often poikilitically enclosed in plagioclase
	crystals,
	- replacement of plagioclase.
Calcite:	- <1% of total mineralogy,
	- secondary filling of cracks.
Textures:	- Medium-grained ( $\circ$ 1.5 - 2.5 mm), allotriomorphic to
	hypidiomorphic granular texture. Cataclastic
	textures such as granulation and undulose extinction
	of the plagioclase are common and the crystals are
	randomly oriented.

Plate: II

PM-1-1 Anorthosite

Major Mineralogy:

Plagioclase: - An<sub>34</sub>?, >90% of total mineral content,

- coarse- to medium-grain size (5-2 mm), subhedral crystals,
- granulated rims, bent or kinked twin lamellae common,
- undulose zonation common in many crystals,
- accessory minerals commonly poikilitically included

in plagioclase crystals.

Accessory Mineralogy:

Epidote, Clinozoisite:	- <7% of total mineral content,
	- generally anhedral, fine-grained (0.5 - 0.25 mm)
	crystals; often as thin veinlets.
Muscovite:	- <3% of total mineral content,
•	- fine-grained, commonly occurring as poikilitic
	laths in plagioclase.
Textures:	- Coarse- to medium-grained ( ${\sim}5-3$ mm), hypidiomorphic
	granular texture. Crystals are randomly oriented and
	granulation is common on plagioclase grain boundaries.
	Accessory minerals commonly grow between grain bound-

aries and occasionally as veinlets and especially in zones of intense granulation.

Plate: III

```
PM-2-3A Anorthosite
```

.

Major Mineralogy:	
Plagioclase:	- An <sub>38</sub> , >90% of total mineral content,
	- medium-grain size (average 2 mm, up to 3.5 mm),
	subhedral crystals,
	- minor granulation of rims, slightly bent crystals,
	- moderately to highly sericitized.
Accessory Mineralo	pgy:
Epidote, Clinozoisite:	- <5% of total mineral content,
	- alteration product of plagioclase,
	- fine-grained, anhedral grains.
Chlorite:	- <2% of total mineral content,
	- fine-grained.
Biotite:	- <2%,
	- fine-grained, somewhat chloritized laths.
Muscovite:	- <1%,
	- very fine-grained,
	- chlorite, biotite, muscovite and epidote commonly
	grow intimately together in cracks between the
	plagioclase grains.
Textures:	- Medium-grained (1.5 - 2.5 mm), equigranular, hypi-
	diomorphic granular texture. Crystals randomly
	oriented and there is minor granulation of the crystal
	rims (plus some minor bending of plagioclase crystals).
	Accessory minerals commonly as poikilitic inclusions
	in the plagioclase crystals.

PM-2-6 Anorthosite	(non-cataclastized)
Major Mineralogy:	
Plagioclase:	- An <sub>47</sub> , >90% of total mineral content,
	<pre>- medium-grained (average 1.5 - 2 mm), anhedral  (some subhedral crystals),</pre>
	- rounded to subangular grain contacts,
	- minor sericitization.
Hornblende:	- <5% of total mineral content,
	- brown to green in PP1,
	- minor chloritization of rims,
	- growth appears to have been at the expense of surrounding plagioclase,
	- medium-grained (<2 mm).
Accessory Mineralog	ју:
Quartz:	- <3% of total mineral content,
	- occur mainly as fine-grained (<0.75 mm), rounded,
	anhedral crystals included in plagioclase crystals.
Epidote,	
Zoisite, Clinozoisite:	- <2% of total mineral content,
	- fine-grained (<0.5 mm) anhedral grains,
	- often poikilitically enclosed in plagioclase grains
	or growing at plagioclase grain boundaries,
	- minor (<<0.5%) associated muscovite.
Textures:	- Medium-grained ( 1.5 - 2 mm) anorthosite with a
	hypidiomorphic granular texture. Plagioclase crystals
	randomly oriented but no cataclastic textures, such
	as granulation, are evident. Minor secondary quartz
	often forms poikilitic inclusions in the plagioclase
	matrix.
Dlata mea	

Plate: IV

K15-0020 Altered Anorthosite

Major Mineralogy:

Plagioclase:	- An <sub>33</sub> , 70% of total mineral content,
	- subhedral to anhedral, medium-grained (0.5 - 1 mm),
	- minor poikilitic inclusions of fine-grained
	sericite, muscovite and quartz,
	- moderate alteration to sericite.
Quartz:	- up to 15-20% of total mineral content,
	- secondary in nature, filling openings in the
	original rock,
	- anhedral crystal form; irregular, rounded boundaries.
Accessory Mineral	०ду :
Chlorite:	- 5-7% of total mineral content,
	- fine-grained, usually <0.5 mm,
	- found in cracks between plagioclase grains.
Epidote:	- <1% of total mineral content,
	- fine-grained (0.25 - 0.5 mm),
	- replacement of plagioclase.
Textures:	- Fine- to medium-grained (0.5 - 1.5 mm) anorthosite
	with a hypidiomorphic granular texture (of plagio-
	clase). Secondary minerals are usually finer-grained
	(<0.5 mm) and are subhedral to anhedral. Minor
	kinking or bending of some crystals is the only
	evidence of cataclasis and all plagioclase crystals

are randomly oriented.

Plate: V

- 69 -

K15-0551 Hornblende Anorthosite

Major Mineralogy:

Plagioclase:	- $An_{37}$ , >70% of total mineral content,
	- medium- to fine-grained but intense sericitization
	masks grain boundaries and twinning.
Hornblende:	- <25% of total mineral content,
	- blue-green type in PPl, often chloritized,,
	- forms bands up to 6 mm across,
	- opaques (magnetite?) occur associated with the
	hornblende, commonly making up 2-3% of the bands.

Accessory Mineralogy:

<3% of total mineral content,
usually fine-grained (<0.5 mm), lath-shaped
crystals occurring between plagioclase and
nornblende grains.

Epidote, Clinozoisite:	- <1% of total mineral content,
	- very fine-grained.
Textures:	- Medium- to fine-grained ( $0.5 - 1.5 \text{ mm}$ ), allotrio-
	morphic granular texture. Banding of hornblende
	(bands up to 6 mm across) common, as is minor
	granulation of the plagioclase.

Plate: V

B) Gneiss

K15-0530 Augite-Hypersthene Gneiss

Major Mineralogy:

Plagioclase: - $An_{60}$ , $\sim$	/55%	of	total	mineral	content,
-----------------------------------	------	----	-------	---------	----------

- well-developed granoblastic, polygonal texture,
  - equigranular, medium- to fine-grained (1 0.5 mm),
  - very little sericitization.

Augite,

- Hypersthene:  $\sim$ 40% of total mineral content, equal amounts of both, granular,
  - both pyroxenes are fine-grained (augite usually larger than hypersthene) and are aligned in bands to form a poor foliation,
  - no exsolution textures in either pyroxene.

Accessory Mineralogy:

Hornblende:	- <5% of total mineral content,
	- green to brown in PPl, often chloritized,
	- subhedral, fine-grained crystals,
	- minor opaques (magnetite) associated with the
	hornblende.
Textures:	- Fine- to medium-grained (0.25 - 0.5 mm), generally
	equigranular, with well-developed granoblastic, pol

equigranular, with well-developed granoblastic, polygonal textures. Grains aligned along an axis of preferred orientation and banding of the pyroxenes and of the feldspars is well-developed.

Plate: VI

K15-0531 Hornblende-Plagioclase Gneiss

Major Mineralogy:

Plagioclase:	- An <sub>54</sub> , 70-75% of total mineral content,				
	- polygonal crystals about 1 mm grain size but				
	up to 3 mm,				
	- minor sericitization,				
	- minor quartz associated.				
Hornblende:	- <15% of total mineral content,				
	- subhedral, medium-grained crystals (<2 mm),				
	- moderately chloritized, but some grains are				
	well-preserved with well-developed cleavage.				

Accessory Mineralogy:

Biotite:	- <3%,
	- deep-brown color in PP1,
	- small laths up to 1 mm long, associated mainly
	with hornblende bands,
	- minor accessory muscovite associated with the
	biotite.
Textures:	- Variable grain size from medium- to fine-grained
	(3 mm to <0.25 mm) with an average grain size of
	about 1 mm. Well-developed granoblastic, polygonal
	textures are present and ellipsiodal inclusions
	(<4 mm across) of very fine-grained, polygonal
	crystals (feldspar, quartz, pyroxene?) are common.
	Hornblendes have a weakly developed banded texture.

Plate: VII

C) Amphibolite

PM-2-4 Banded Amphibolite

Major Mineralogy:

Hornblende:

- \65% of total mineral content,

- dark green in PP1, occasionally chloritized,

- subhedral to euhedral grains, up to 2 mm long in the bands,
- minor magnetite associated with the hornblende bands.

Plagioclase:

- An<sub>54</sub>, ~30% of total mineral content,
  - fine-grained, polygonal, granoblastic textures are well-developed,

- low to moderate sericitization.

Accessory Mineralogy:

Epidote, Clinozoisite: - <2% of total mineral content,

> - very fine-grained, alteration of plagioclase crystals, sometimes form thin mantles around the plagioclase crystals.

Textures:

- Fine- to medium-grained (0.5 - 1.5 mm) with a welldeveloped granoblastic, polygonal texture. Welldeveloped banding of hornblende and of plagioclase.

Plate: IX

D) Mylonite

PM-2-9

Mineral Content:

Quartz:	-	forms	most	porphyroblasts	(<2	mm )	undulose
		extind	ction	common,			

- also makes up fine-grained matrix,

 some symplectic growth between rare plagioclase porphyroblasts and matrix quartz; porphyroblasts often have rounded, granulated or embayed grain boundaries.

Quartz, K-feldspar, Plagioclase:	- commonly fine- to very fine-grained matrix minerals.
	- plagioclase forms some of the smaller porphyroblasts.
Muscovite:	- forms well-developed foliation bending around
	porphyroblasts,
	- very fine-grained.
Magnetite:	- very fine-grained, associated with muscovite
	foliation.
Textures:	- Well- developed mylonitic texture with foliation
	wrapped around the porphyroblasts. The matrix is
	fine- to very fine-grained and partially recrystal-
	lized. The porphyroblasts are up to 2 mm across
	and are usually elliptical and elongate parallel
	to foliation. The matrix accounts for 70% of the
	total rock.

Plate: VIII

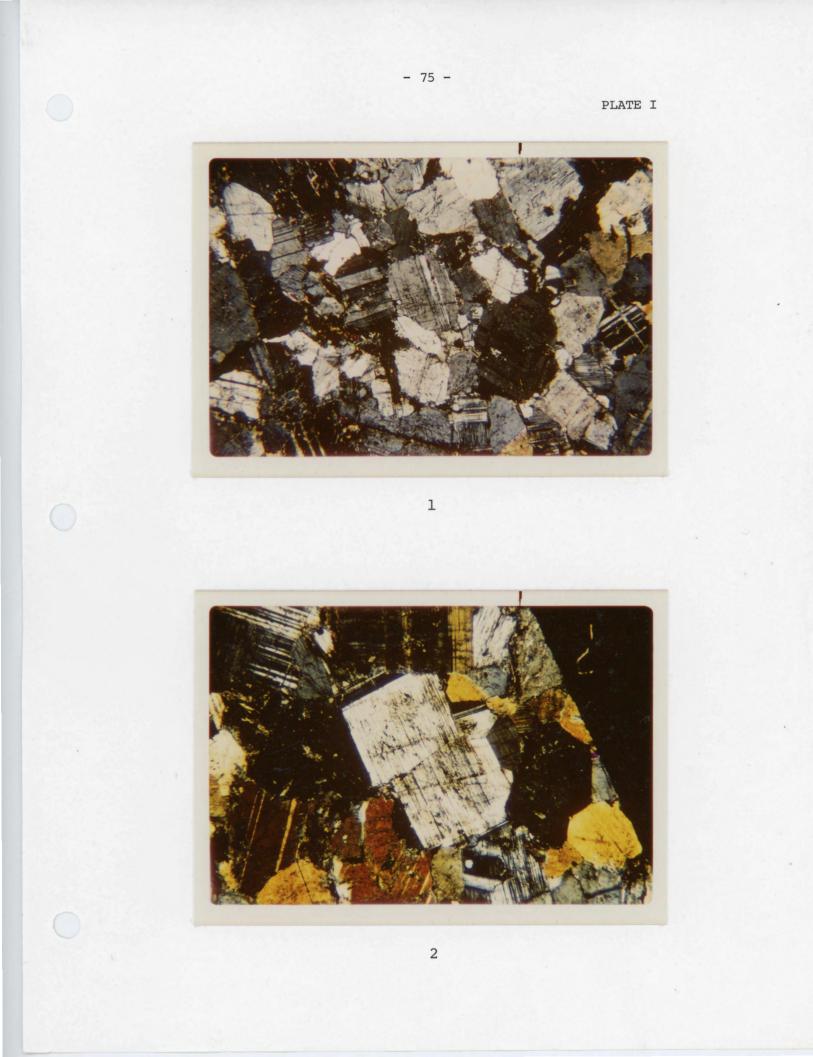
# PLATE I

Figure 1. K15-0520 Anorthosite Mag 10X (X-nicols)

 medium-grained, subhedral plagioclase crystals with minor granulation and accessory minerals (epidote, chlorite, muscovite) on rims.

Figure 2. K15-0520 Anorthosite Mag 16X (X-nicols) (slide thickness  $$>30\mu)$ 

- fractured plagioclase crystal; minor granulation on other plagioclase crystals.



## PLATE II

Figure 1. K15-0522 Anorthosite Mag 16X (X-nicols) (slide thickness >30µ)

bent and granulated subhedral plagioclase crystalsminor sericitization.

Figure 2. K15-0548 Anorthosite Mag 10X (X-nicols)

 highly altered (sericite, epidote, chlorite veins, muscovite) anorthosite.

- granulated plagioclase crystals.



## PLATE III

Figure 1. PM-1-1 Anorthosite Mag 10X (PPL)

- moderately sericitized (black) plagioclase (white) with some epidote veins (brownish grey)

Figure 2. Same as above (X-nicols)

- epidote, muscovite alteration minerals in granulated plagioclase.



## PLATE IV

Figure 1. PM-2-6 Anorthosite Mag 10X (X-nicols)

- anhedral, randomly oriented plagioclase with minor intergrown hornblende
- minor quartz blebs (Q) and epidote.
- Figure 2. PM-2-6 Anorthosite Mag 10X (X-nicols)
  - same as above.



### PLATE V

Figure 1. K15-0020 Altered Anorthosite Mag 10X (X-nicols) (slide thickness >30µ)

- fine- to medium-grained subhedral plagioclase (P) with up to 20 percent secondary quartz (Q) and minor muscovite (pink).

Figure 2. K15-0551 Hornblende Anorthosite Mag 10X (X-nicols)
 - extremely sericitized plagioclase (brownish grey) and
 medium-grained blue-green hornblende (with associated mag-

netite (black) ).

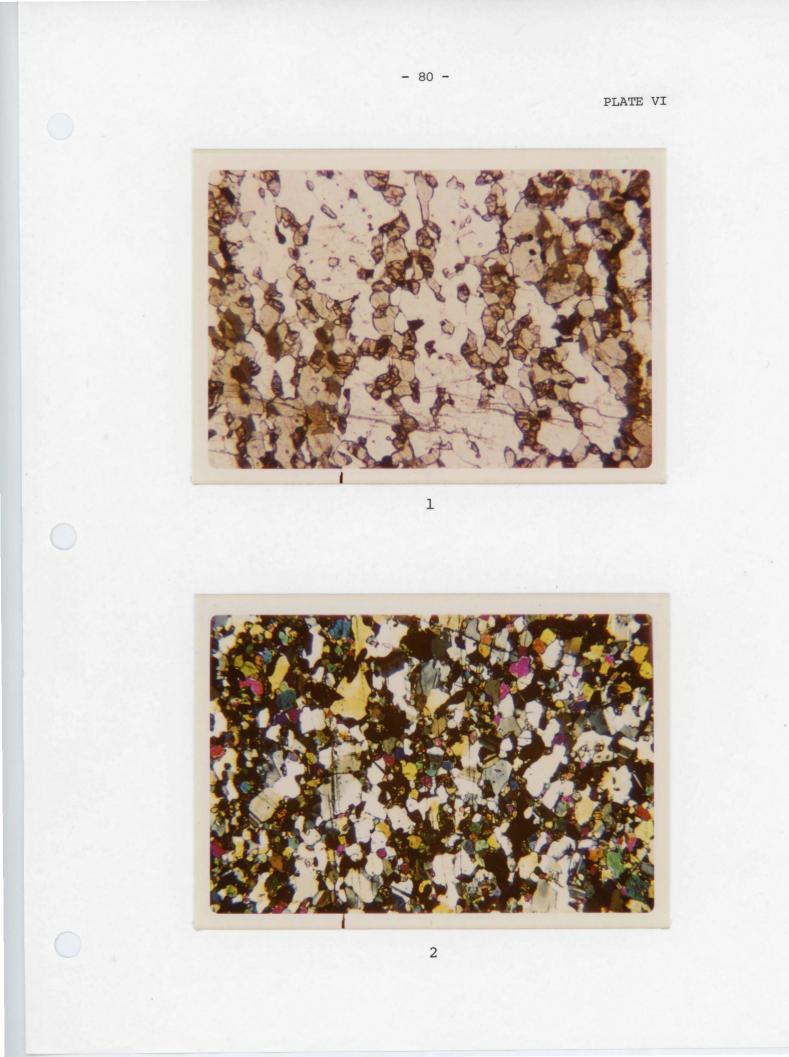


# PLATE VI

Figure 1. K15-0530 Augite-Hypersthene Gneiss Mag 16X (PPL)

- equigranular, banded pyroxenes and feldspar (white)
- coexisting, granular augite (pale green) and hypersthene (pink).

Figure 2. K15-0530 Augite-Hypersthene Gneiss Mag 16X (X-nicols)
 - well-developed granoblastic polygonal textures (plagioclase-white; pyroxenes-higher colors).



### PLATE VII

- Figure 1. K15-0531 Hornblende-Plagioclase Gneiss Mag 10X (X-nicols)

  plagioclase (slightly sericitized) (white) with lesser
  amounts of medium-grained hornblende (green) and associated
  lath-shaped biotite (deep reddish brown).
- Figure 2. K15-0531 Hornblende-Plagioclase Gneiss Mag 13X (X-nicols) (slide thickness >30µ)
  - granoblastic, polygonal textures developed in the plagioclase crystals.
  - nodule of fine-grained polygonal plagioclase, quartz crystals and minor muscovite and pyroxene?; the nodule may have originally been a hornblende grain.



### PLATE VIII

Figure 1. PM-2-9 Mylonite Mag 10X (X-nicols)

quartz porphyroblasts up to 3 mm across aligned parallel
 to foliation developed in a fine-grained matrix of quartz,
 K-feldspar, muscovite, plagioclase.

Figure 2. PM-2-9 Mylonite Mag 10X (PPL)

- well-developed mylonitic texture, numerous ellipitical porphyroblasts of quartz aligned parallel to foliation.



# PLATE IX

Figure 1. PM-2-4 Banded Amphibolite Mag 10X (PPL)

- bands of hornblende (up to 1 mm across) (dark green) and granoblastic plagioclase (white)
- edges of many hornblende grains are chloritized (pale green).



#### APPENDIX II Analytical Methods

#### Rare Earth Element Determination

The technique employed in this study to determine REE contents in the samples was instrumental neutron activation analysis (INNA). Approximately 0.6 grams of powdered rock was packed in pure silica tubes wrapped with a weighed Fe wire to act as a flux monitor. The samples and 3 standards plus a blank were irradiated for approximately five hours at 1 Megawatt power (flux approximately  $5 \times 10^{12} n/cm^2 sec$ ) in the McMaster Nuclear Reactor, Hamilton, Ontario. The flux from the samples was counted on two Ortec 48 cm<sup>3</sup> Ge(Li) coaxial detectors with NIM standard modular instrumentation, located in the National Research Council Building, Halifax, Nova Scotia. The resolution of the two detectors in the system is about 2.2 KeV at 1332 KeV. A 4096 channel Nuclear Data model 50/50 pulse height analyser is used to store the amplifier signals and a PDP-8/L is used as the on-line computer. Spectra are counted over the range 60 to 1660 KeV on 2048 channels and a PDP-12 computer is used for off-line data processing.

Precision and accuracy are measured using the two U.S.G.S. AGV-1 and U.S.G.S. BCR-1 standards. A comparison of the results for these two samples in this study with those from other studies is shown in Table II-1. The relative precision for the analysed REE elements are given below:

REE	Relative Precision (%	5)
La	0.86	
Ce	0.23	
Nd	5.17	
Sm	1.61	
Eu	1.12	
Tb	1.69	
Yb	7.07	
Lu	0.55	

The degree accuracy for the Nd values is very poor and therefore should be omitted in the final analysis of the samples (Muecke, G., pers. comm., 1979).

SAMPLE	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu ppm	Refer- ence
AGV-1	34	63	41	5.99	1.68	0.69	1.83	0.28	this work, 1979
	35	62	37	5.8	1.72	0.71	1.59	0.29	this work, 1979
	43	72		6.62	1.68	0.65	1.28	0.29	Green et al. 1972
	33	57		5.4	1.55	0.77	1.6	0.37	Gordon et al. 1968
	35	63	39	5.9	1.7	0.70	1.7	0.28	Flana- gan,1973
BCR-1	27	54	41	7.8	2.51	1.05	3.83	0.55	this work, 1979
	23	46		5.9	1.95	1.0	3.2	0.60	Gordon et al. 1972
	26	53.9	29	6.6	1.94	1.0	3.36	0.55	Flana- gan,1973

Table II-1: REE abundances in the standard sample AGV-1 and BCR-1 with comparison to other workers.

\*

#### Electron Microprobe Analysis

A determination of the chemical composition of individual minerals and whole rock samples was made using the Cambridge Mark V Microprobe at Dalhousie University. The microprobe has an Ortec energy dispersal system and operates under 15Kv EHT with a 15na probe current. The software program is EDATA from Smith and Gold of the University of Alberta. The geological standards used in most cases were: a) Mn 96189 - a manganese standard; b) K-K-Kaersutite (an amphibole); c) Albite and d) ILM-ilmenite.

Mineral compositions were determined on polished thin sections  $(\sim 30\mu$  thick) which were precoated with a carbon film. At least six analyses, each on a different grain of the mineral in question (eg. plagioclase, pyroxene), in each thin section were made to determine any variation in the composition of the mineral. The accuracy of the results for the major elements is between 1.5-2.0 percent of the amount present and the detection limit for most elements, except Na and Mg, is approximately 0.1%. The detection limits for Na and Mg are 0.3% and 0.2% respectively.

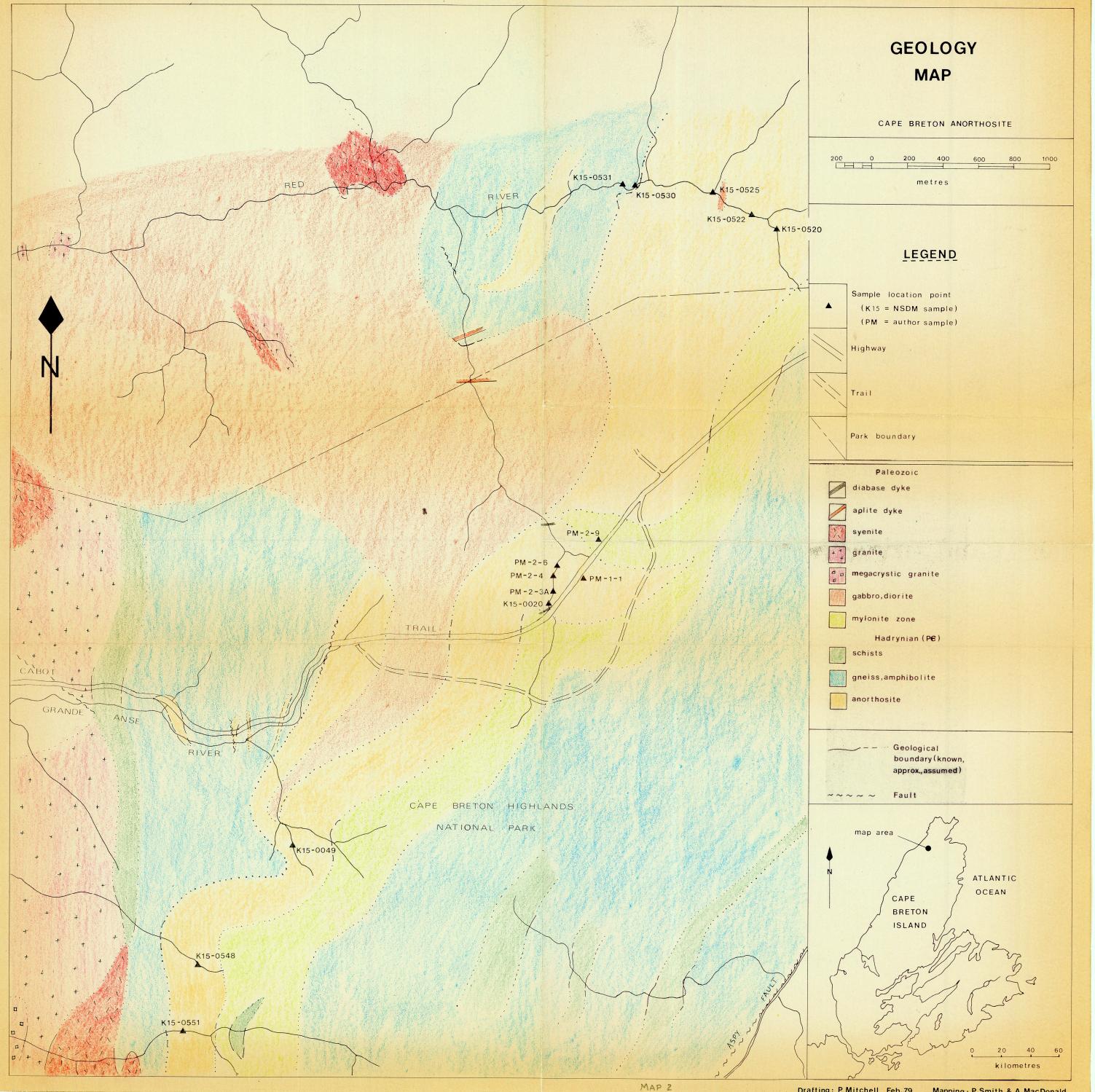
Whole rock compositions were determined on glasses made by tantalum-strip fusion of the rock powders in question. At least six different points on each sample were probed in order to obtain an average composition for the sample. The accuracy and precision for the results on U.S.G.S. standard BCR-1 are given in Table II-2.

- 87 -

ELEMENT	WEIGHT PERCENT	PRECISION (%)	ACCURACY	
si02	54.50	<u>+</u> 1.1%	<u>+</u> 1.6%	
Ti02	2.61	+ 4.6%	<u>+</u> 16.5%	
A1203	13.45	<u>+</u> 1.3%	- 2.8%	
Fe0(+Fe <sub>2</sub> 0 <sub>3</sub> )	12.85	+ 6.2%	+ 4.3%	
MnO	0.10			
Mg0	3.66	+ 5.1%	+ 3.9%	
Ca0	7.28	<u>+</u> 2.5%	+ 3.6%	
Na <sub>2</sub> 0	2.92	<u>+</u> 4.1%	- 13.7%	
к <sub>2</sub> 0	1.68	<u>+</u> 6.0%	- 2.9%	

Table II-2: Precision and accuracy for the elements in the whole rock (glass) analysis of U.S.G.S. BCR-1 for the Dalhousie University microprobe.

			lt



Drafting: P. Mitchell Feb. 79

Mapping : P. Smith & A. MacDonald

