PALEOTECTONIC ENVIRONMENT OF THE NORTH MOUNTAIN BASALT, NOVA SCOTIA: A GEOCHEMICAL APPROACH

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CHAPTER 1

INTRODUCTION

Triassic rocks of the Maritime Provinces occur mainly in the lowlands surrounding the Bay of Fundy. The rocks are predominantly fluvial and lacustrine deposits (Crosby, 1962; Klein, 1962) which are interbedded with volcanic extrusives.

The volcanic rocks of North Mountain occur in a roughly linear belt outcropping in Digby, Annapolis and Kings Counties, Nova Scotia. The physiographic North Mountain includes sediments of the Annapolis and Scots Bay Formations as well as the basalts. These rocks are geologically, structurally, and topographically continuous from Cape Blomidon to Brier Island, a distance of about 209 km. (Fig. 1). The name North Mountain was applied by Powers in 1916 while conducting the first regional study of the Maritime Triassic rocks. Isolated outcrops of basalt occur on the northern shores of Minas Basin at Economy Mountain, McKay Head, Clark Head, Wasson's Bluff, Partridge Island, Five Islands, Cape Spencer, Cape Sharp, Cape D'Or and Ile Haute.

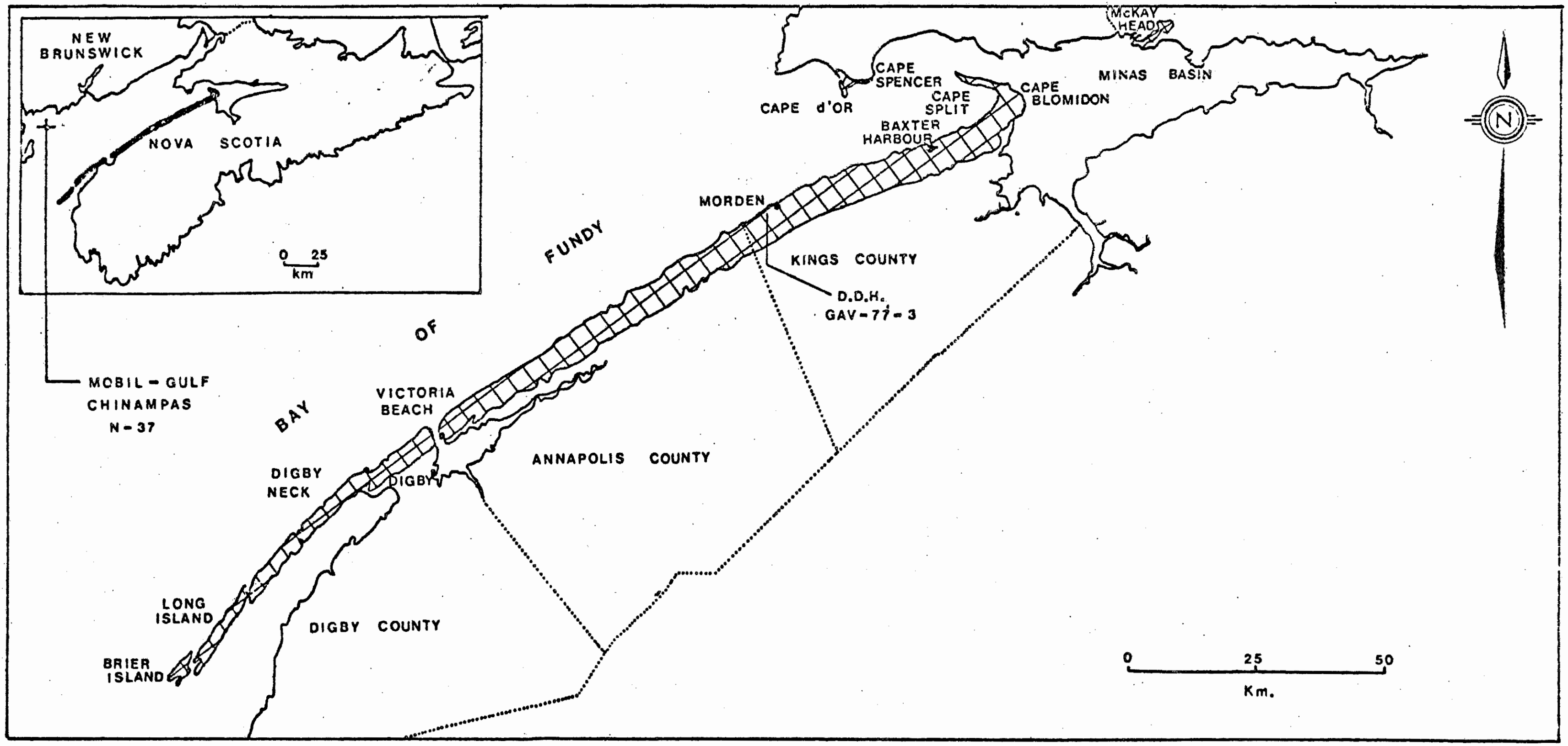

Figure 1

Location map showing the North Mountain Basalt and the location of the drill holes (Modified after Sinha, 1970).

In addition to rocks sampled from North Mountain, basalt chips recovered from an exploration well jointly drilled by Mobil-Gulf were studied. The location of the hole is shown on the inset diagram of Figure 1.

Aim of the Thesis

The theory of plate tectonics recognizes that various tectonic environments have characteristic types of igneous activity and magma genesis. Tectonic environment appears to control the type of material melted, the degree of partial melting and the amount of differentiation. These variables acting over the imposed physico-chemical constraints of a system will ultimately determine the type of igneous rock formed.

Recently, it has been shown that the geochemistry of igneous rocks may indicate the tectonic environment in which they were formed. Samples collected from different environments of known tectonic affinity have been compared and results of these studies indicate that certain elements can be used to discriminate between the various environments.

The purpose of this study is to analyse the North Mountain basalts for the various elements believed to be discriminators and then to use these elements in an attempt to determine the paleotectonic environment of eruption. Since these basalts can have only one environment of eruption, it is also a check on the consistency of the various discriminating techniques.

Previous Work

One of the first geological investigations of the North Mountain area was conducted by Dawson (1855). He observed an angular unconformity between the Acadian red beds and the underlying Paleozoic rocks. On the basis of palaeontological evidence, he postulated a Triassic age for the red beds. In 1858 he described the lava flows between Cape Blomidon and Brier Island. The first microscopic description of these basalts was made by Marsters (1890).

Powers (1916) made the first regional stratigraphic study of the Triassic sediments and proposed the following units for Nova Scotia.

Newark Group
    Scots Bay Formation
    North Mountain Basalt
    Annapolis Formation
        Blomidon Shale Member
        Wolfville Sandstone Member
UNCONFORMITY
    Paleozoic rocks

Powers and Lane (1916) made a detailed microscopic study of the lowest basalt flow at Cape Spencer (Fig. 1). They also published results of a seven hole diamond drilling project at Cape D'Or in the same year.

Crosby (1951) described the Scots Bay Formation and the general character of the lava flows in the Wolfville map area (GSC Map 1128A).

Klein (1957, 1960) described and mapped the Acadian Triassic sediments as well as the lava flows. Baird and Take (1959) discovered reptilian remains in the Annapolis Formation which confirmed a Triassic age.

Hudgins (1960) examined the basalts, interflow sediments and clastic dikes between Baxter Harbour and

Victoria Beach and deduced that there were six flows.

Klein (1962) proposed that the Blomidon and Wolfville Members be raised to Formational status and the Annapolis Formation as defined by Powers (1916) be dropped as a rock-unit name. He also proposed (1960) that the term Newark had been applied to the Maritime provinces in a time-stratigraphic sense and instead suggested the name Fundy Group be adopted.

The physical and chemical properties of the zeolites from North Mountain were investigated by Walker and Parsons (1922). The zeolites have been more recently studied by Aumento (1965) and Aumento and Friedlander (1966).

The Nova Scotia Department of mines undertook a four hole diamond drilling program in North Mountain in 1966 for Sladen, Quebec Ltd. The drill target was Cu mineralization in the basalts.

Carmichael and Palmer (1968) determined the age of the North Mountain Basalt to be 200 ± 10 Ma on the basis of four whole rock K-Ar determinations. This age was based on the old decay constants for potassium and becomes approximately 204 Ma when the new potassium decay constants $\lambda_\varepsilon = 0.581 \times 10^{-10}y^{-1}$, $\lambda_\beta = 4.962 \times 10^{-10}y^{-1}$, are applied (P.H. Reynolds, Personal communication, 1979).

Poole et al. (1970) report a K-Ar age of 198 Ma for the basalts which becomes 202 Ma when the new constants are applied.

Sinha (1970) states there are four main basalt flows in North Mountain. His petrological study of the basalt shows the rocks are tholeiitic and he reports the co-existence of three pyroxene minerals in several samples.

Burton (1972) investigated the intrusives near Goshen, Guysborough County and suggested this may have been the basalt source which has since been offset by a major dextral fault. He also attempted to correlate the Triassic basalts of Nova Scotia with the Eastern North American (E.N.A.) tholeiites along the eastern margin of the United States.

Smitheringale (1973) discussed the nature and occurrences of the basalt in the Bridgetown and Digby map areas (N.T.S. Maps 21-A-14, east half; 21-A-15, west half and 21-A-12, east half).

Vilks (1978) investigated the Cu content of the North Mountain Basalt and states that native Cu occurs in trace quantities associated with zeolites and in some fault zones.

Microfossils recovered from the Mobil-Gulf Chinampas N-37 well indicate an age of Upper Triassic to Lower Jurassic for the basalts.

The present study was based on examination of twelve basalt samples obtained from the drill core which penetrated the North Mountain and several well chip samples recovered from the Mobil-Gulf hole in the Bay of Fundy. Samples from the Bay of Fundy were not as extensively studied as the North Mountain basalts. The North Mountain Basalt samples were analysed for all major elements, numerous minor and trace elements and rare earths. Thin sections were examined petrographically and several polished thin sections were used to analyse augite crystals with the electron microprobe. Mobil-Gulf samples were examined petrographically and augite crystals were examined with the electron microprobe. Trace elements were also determined for several Mobil-Gulf samples.

The chemical data were compared to see any inter and/or intraflow variations. Various elements believed to be discriminators of tectonic environment were plotted on their respective diagrams. The diagrams were then compared to get an indication of the tectonic environment of eruption of the North Mountain Basalt.

CHAPTER 2

FIELD WORK

Field work consisted of sampling and logging of material recovered from exploratory drill holes.

Diamond drill core obtained from a hole 3 km. west of Morden, Nova Scotia, by Getty Mines Limited, and stored under the authority of the Geology Department at Acadia University, was examined and logged on May 12, 1978. Sections of the core believed to be suitable for sampling were noted and on May 18, 1978, these sections were split for petrographic work and chemical analysis.

Several days were spent in the Public Examination room of the Federal Government Department of Energy, Mines and Resources, branch located at the Bedford Institute of Oceanography, Dartmouth, Nova Scotia. The purpose of the visits was to examine and collect basalt rock fragments recovered from the Mobil-Gulf Chinampas N-37 rotary drill hole. The locations of the drill holes are shown in Figure 1.

Core samples are preferable to samples collected from surface outcrop because the chemical effects of subaerial weathering are minimized. It is important in a study of this type that the least altered material be sampled in an effort to ensure that the geochemistry of the rocks be as close as possible to the original magma composition at the time of solidification. For this reason, sampling of the core was biased towards the freshest material. Obviously oxidized flow tops and amygdaloidal material were rejected in favor of more compact, gray to black basalt which appeared to be least altered, megascopically.

A drill hole also provides a unique opportunity to sample an entire basalt sequence at one locality, but this does not imply that the sequence has been sampled at regular intervals from top to bottom. Stratigraphic columns for the drill holes are shown on Figures 2 and 3. Sample locations are also shown. In the case of the North Mountain, each sample analysed was examined petrographically whereas for the Chinampas N-37 samples, petrographic work was done only on three samples collected from the cored interval shown in Figure 3. An expanded view of this section and sample locations are shown in Figure 4.

Field Relations

Actual field relations were not studied by the author with the exception of the basalt flows exposed along Cape Split (Fig. 1). Field relations are well documented by Crosby (1951), Klein (1962), Sinha (1970) and Smitheringale (1973).

The basal sedimentary unit of the Triassic rocks in this region is the Wolfville Formation which unconformably overlies Paleozoic rocks (Crosby, 1951). This Formation consists predominantly of sandstone and arkose with conglomerates at the base. The thickness ranges from 61 metres in Colchester County to 366 metres in the type area with a maximum of about 762 metres in Annapolis County (Klein, 1962). The Blomidon Formation conformably overlies and interfingers with the Wolfville Formation. The Blomidon Formation consists of fine grained sandstone, claystone and siltstone. It ranges in thickness from about 8 metres at Central Clarence, Annapolis County to 366 metres at the type section in Kings County.

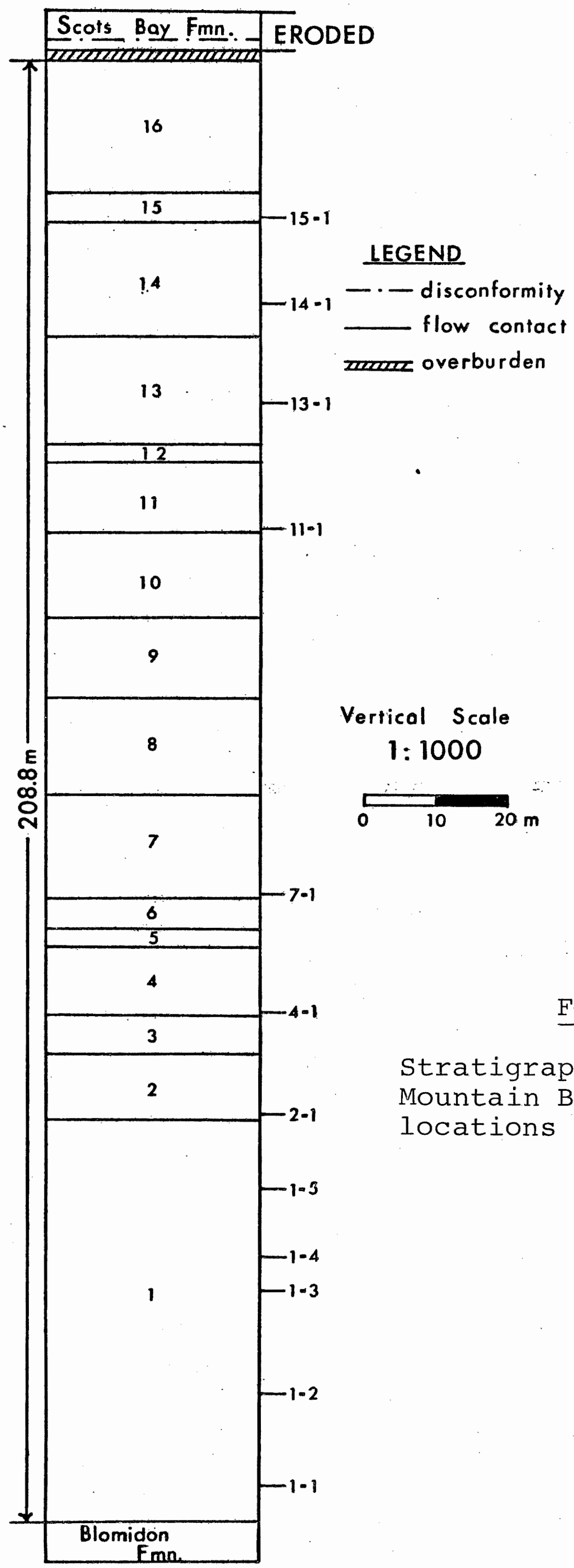

Figure 2

Stratigraphic column of North Mountain Basalt showing sample locations and flow distribution.

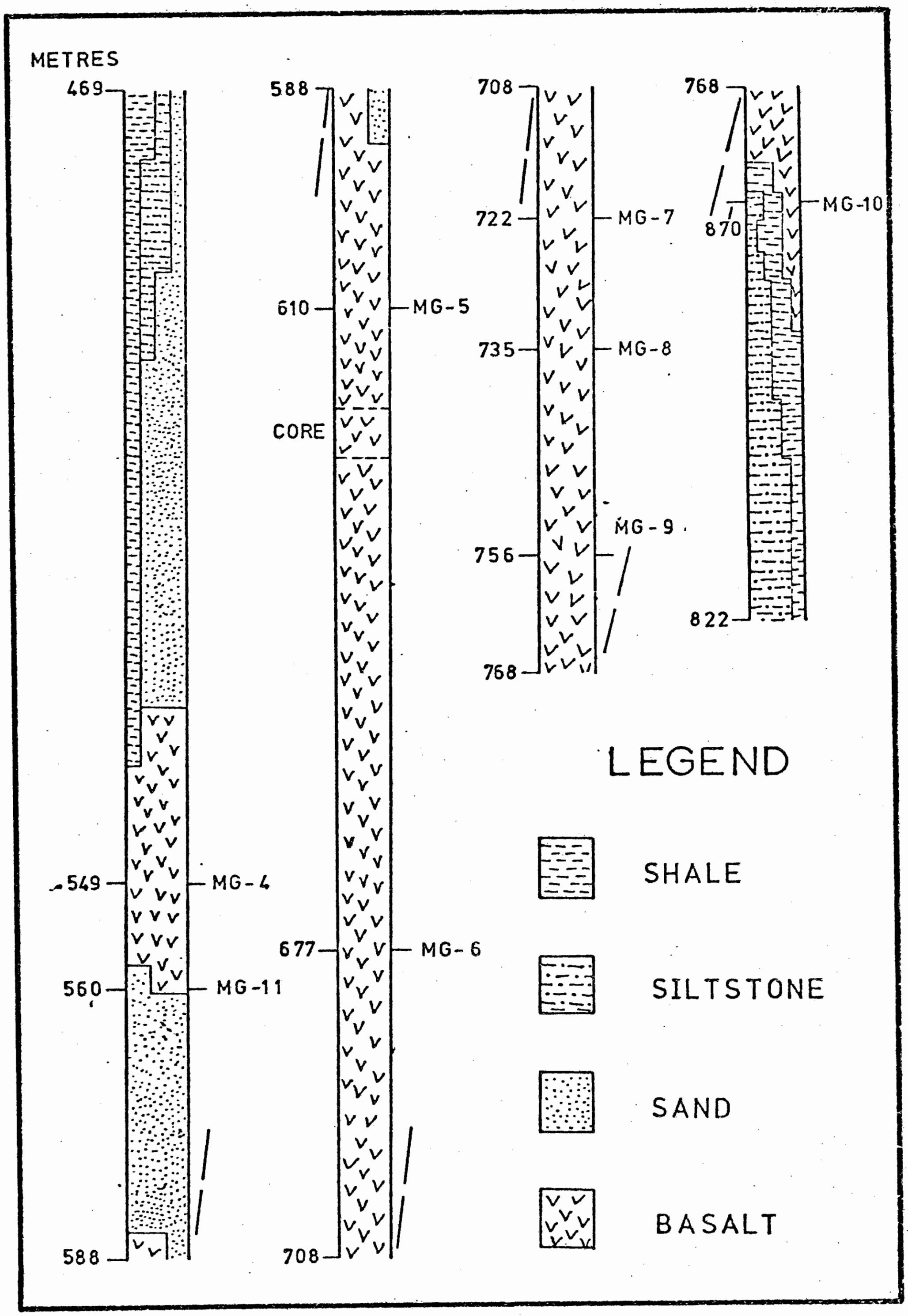

Figure 3

Stratigraphic column of the Mobil-Gulf Chinampas N-37 well showing the location of the MG samples.

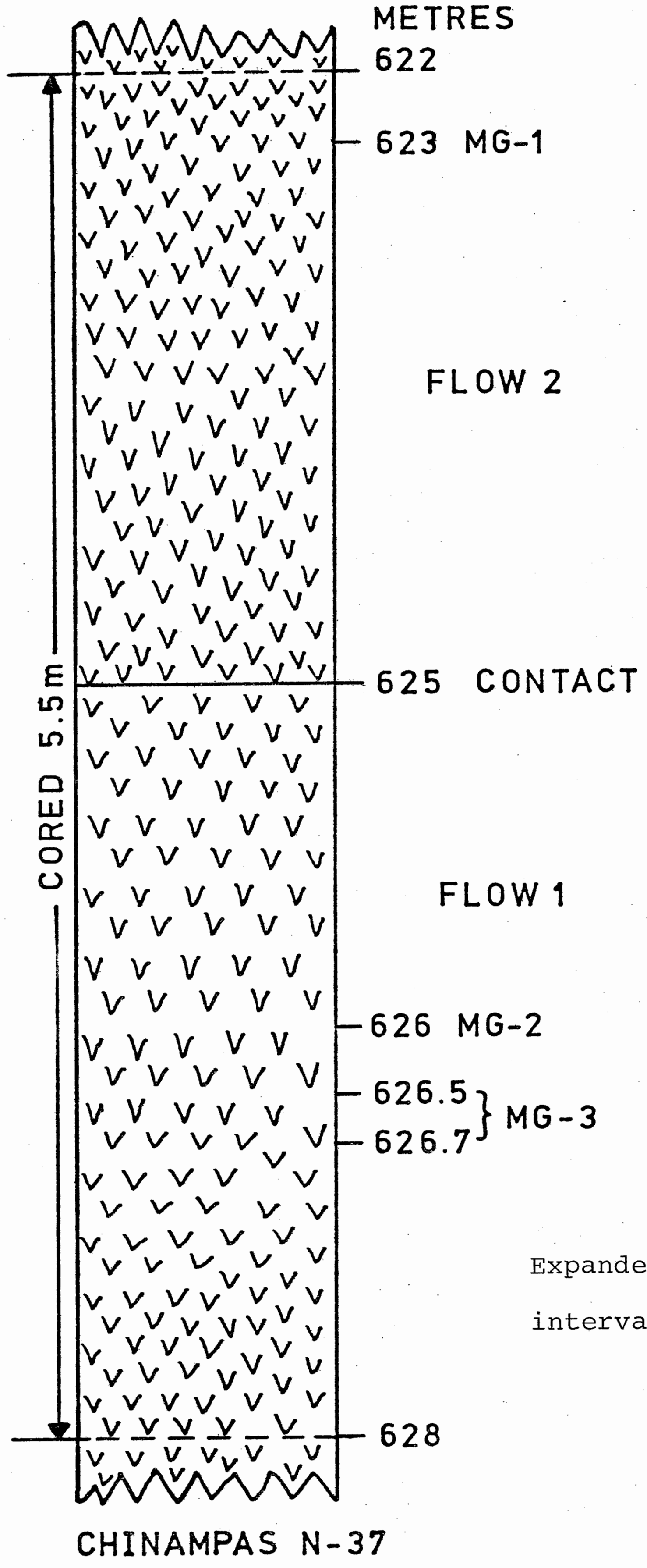

Figure 4

Expanded section of the cored interval shown in Fig. 3

Detailed stratigraphy is reported by Klein (1962).

Conformably overlying the Blomidon Formation is the North Mountain Basalt. Considerable controversy exists as to the actual number of flows, and the thickness of the Formation is variable. Klein (1957) reported sixty-six volcanic flows but this figure was subsequently reduced to sixteen (Klein, 1960 as per Sinha, 1970). No explanation is proposed for the difference in the number of flows reported in 1957 and 1960. Klein (1962) reports a thickness of 267 metres of basalt and dolerite consisting of sixteen flows at the type section in Kings County.

Crosby (1962) states that basalt flows totalling 274 metres in thickness and having a width of about 6.5 kilometres occur in the Wolfville map area (G.S.C. Map 1128A). No indication as to the number of flows is given, however, he states there are minor flows on the north shore of the mountain which pinch out laterally and between the flows are, "thin discontinuous layers of green grit composed of material derived from the underlying flow" . These green layers could not be recognized in the core.

Sinha (1970) has proposed that the North Mountain Basalt consists of four major flows and that the volcanic eruptions occurred in two distinct phases separated by a short time interval. The earliest phase includes the 'Blomidon Flow' and the two 'Cape Split Flows' which are separated from the overlying 'Scots Bay Flow' by sediments. Sinha (1970, p. 5) states that these interflow sediments are continuous throughout the North Mountain but a complete cross section was not provided as evidence. No thickness was reported for the entire member.

Smitheringale (1973) reports that six or more conformable flows occurred in his map areas (G.S.C. Maps 1344A, 1345A and 1346A) but the top of the basalt is nowhere exposed. A thickness of 175 metres is reported at Central Clarence (Map 1345A) and approximately 244 metres are reported at Thorne Cove (Map 1344A). Lollis (1959, as per Smitheringale, 1973) gives a maximum thickness of about 274 metres for a section at Petit Passage on Digby Neck.

Stevens (1975) reports a thickness of 235 metres of basalt near Cape Blomidon thickening to about 366 metres near Digby Neck, Long Island and Brier Island.

Drill core recovered from the Getty Mines hole (GAV-77-3) three kilometres west of Morden on the Fundy shore show the basalts have a minimum apparent thickness of 210 metres since the top of the basalt has been removed by erosion (Fig. 2).

The well log from the Mobil-Gulf Chinampas N-37 hole indicates a total thickness of 201 metres of basalt were penetrated. These are however in two parts separated by about 125 metres of sandy sediments (Fig.3).

GAV-77-3 Core

The core recovered from this hole drilled by Getty Mines was logged and separated into sixteen (16) distinct flows based on the following criteria:

1) an interflow soil horizon or weathered zone which is fine grained and greenish-gray to gray in colour.

2) amygdaloidal flow tops
3) a massive basal zone
4) a narrow amygdaloidal zone near the base containing smaller amygdules than the flow tops

A lava flow may consist of several separate pulses or sheets of magma that have poured over one another during a single eruption. These successive and essentially contemporaneous pulses which are embodied in a single larger flow are known as flow units (MacDonald, 1967). Flow units are of necessity thinner than the main flow and range in thickness from three to six metres (Shrock, 1948). Flow units are lithologically similar to the main flow and as a result of the similarity it was generally not possible to distinguish flows from flow units when examining the core. In any case, the basalt section at Morden is comprised of sixteen distinct units and this agrees with Klein (1962). If a flow unit is designated as any pulse less than six metres in thickness, the core could be separated into five (5) flow units and eleven (11) flows. Thicknesses of the individual units are given in Table 1 and flow number 1 is stratigraphically the lowest.

TABLE 1 THICKNESS OF THE NORTH MOUNTAIN FLOWS IN GAV-77-3

Flow	Thickness (m)	Number of samples collected
16	18.8	-
15	4.1	1
14	16.2	1
13	15.5	1
12	2.7	-
11	9.9	1
10	12.2	-
9	11.3	-
8	13.9	-
7	14.9	1
6	4.3	-
5	2.7	-
4	9.8	1
3	5.5	-
2	9.5	1
1	57.5	5
	208.8	12

These basalts are amygdaloidal and their flow tops are invariably oxidized to a reddish or purplish colour. Amygdules are most abundant near the tops and bottoms of the flows but isolated amygdules were observed in the more massive sections of some flows. The amygdules are noticeably larger in the flow tops than they are in the basal zone and they contain a variety of zeolites. One section of the drill core cut part of a pipe vesicle 0.9 metres in length. All vesicles have been filled with zeolites.

Passing stratigraphically downward through a particular flow, the colour changes from an oxidized red-brown to greenish-gray, dark gray or black and from amygdaloidal to massive. The central sections of the thicker flows are slightly coarser grained.

The North Mountain Basalt conformably overlies the Blomidon Formation (Crosby, 1962; Klein, 1962; Smitheringale, 1973). The sediments immediately underlying the basalt are a deep greenish-black colour and appear brecciated and possibly baked. These sediments adjacent to the base of the basalt are also cut by gypsum veins. The greenish-black siltstone passes downward into brick-red siltstone. The greenish black colour may be a consequence of chemical effects when the basalt was extruded. For example, any iron present in the sediments may have been reduced from ferric to ferrous oxidation states. Chemical analyses of these sediments might provide evidence to explain the colour.

Mobil-Gulf Chinampas N-37 Core

The location of this hole is shown in Figure 1 and the exact coordinates are 44°56'53"N and

66°35'17"W. Due to the drilling technique, all the basalt examined was in the form of rock chips with the exception of material recovered from the cored section. This cored interval went from a depth of 622.4 metres to 631.9 metres but only 5.5 metres of basalt were recovered (Fig. 4). Three samples were selected from this core for petrographic work. The core was very reddish in colour and highly amygdaloidal. Based on the criteria presented previously there were partial sections of two adjacent flows present.

The other samples retained and logged by the drilling crew consisted entirely of rock chips. These rock fragments were collected regularly at ten foot intervals. The log for the section of interest is reproduced in Appendix C. Because of the heterogeneity of these samples, the rock chips were washed with water to remove the drilling mud and examined under a binocular microscope. The basalt fragments were separated and collected for further analysis.

Table 2 is a reproduction of the stratigraphy reported in the Mobil-Gulf drill report.

TABLE 2

MOBIL-GULF CHINAMPAS N-37

STRATIGRAPHIC COLUMN

ERA	SYSTEM	FORMATION	INTERVAL (m)	THICKNESS (m)	Diagnostic FOSSILS
MESOZOIC	LOWER JURASSIC	Scots Bay Fm	± 249-453	± 204	Classopollis torosus, C.itunensis, Circulina myeriana, Monsulcites minimus, Vitreisporites pallidus, Cyathidites australis, Todisporites major.
		North Mtn. Basalt	453-785	332	Mostly Barren
	UPPER JURASSIC? LOWER JURASSIC?	Annapolis Group	785-3661	2909+	Core sample at 12004' contains a sparse palynoflora of "generalized Jurassic aspect". Tsugaepollenites mesozoicus, Klavsipollenites spp., Circulina meyeriana

Interflow Sediments

Nowhere in the core of GAV-77-3 were interflow sediments or well developed weathering profiles observed. The continuous interflow sediments reported by Sinha (1970) in North Mountain occur between his 'Cape Split Flow" and the 'Scots Bay Flow' which constitutes the youngest basalt. The absence of interflow sediments in the core of GAV-77-3 has some major implications especially when one considers that Sinha has reported outcrop 0.8 km. west of Morden which contains interstratified sediments 7 to 15 cm. thick (1970, Appendix II A).

The top of the basalt is absent at this location and the amount of material removed by erosion is unknown. If these interflow sediments are continuous throughout North Mountain it implies that the entire 'Scots Bay Flow' as well as the sediments have been removed by erosion at the location where GAV-77-3 was drilled. This would mean the first basalt encountered in the drill hole belongs to Sinha's 'Cape Split Flow'. A second possibility is that no continuous interflow sediments exist and the third possibility is that any sediment present may have been ground up during the drilling process.

Interflow sediments do exist in the Mobil-Gulf Chinampas N-37 hole (Fig. 3). Correlation of these sediments with a possible continuous interflow sedimentary horizon in North Mountain is not justified since there is not enough stratigraphic control in the area. The presence of these sediments does indicate however that this basalt was erupted in two phases separated in time.

Origin and Age of the Basalts

There is at present no conclusive field evidence which identifies the eruptive source of the basalts. Smitheringale (1973) suggests the source of eruption was to the northwest and possibly from the Five Islands region. Burton (1972) has suggested that intrusives near Goshen, Guysborough County might have been the source and have now been displaced by movement on the Glooscap Fault System. Evidence given includes i) similar major element chemistry as well as ii) a large contact aureole around the Goshen intrusives. A large contact aureole suggests the passage of a large volume of magma.

The general thickening of the basalts to the southwest may be a function of proximity to a source area. Stevens (1975) has suggested that fissure type feeders might exist in the Freeport area on Long Island.

The North Mountain Basalt was erupted subaerially. Evidence supporting this statement includes a general absence of pillow lavas and the presence of vaguely defined weathered horizons. The ubiquitous reddened flow tops are also indicative of subaerial eruption (Shrock, 1948). Sinha (1970) has reported pillow lavas from several localities which he has interpreted to be the result of lava flowing into a subaqueous environment. Vilks (1978) has suggested the pillows reported by Sinha represent various degrees and stages of spheroidal weathering in which the columnar joints have been altered or filled with chert.

The age of North Mountain is Upper Triassic-Lower Jurassic. The basalts are bracketed by sediments containing Isoura ovata (Klein, 1962). The presence of the latter along with fish remains indicates a Triassic age for the Scots Bay Formation. The diagnostic fossils listed in Table 2 indicate an Upper Triassic-Lower Jurassic age. Whole rock K-Ar methods give ages consistent with paleontological evidence. Carmichael and Palmer (1968) give an average age of 204 Ma and Poole *et al*. (1970) give an average of 202 Ma. These are the corrected ages obtained by applying the new potassium decay constants. The boundary between Triassic and Jurassic falls at 212 Ma (Armstrong, 1979) therefore the basalts are Lower Jurassic based on the revised time scale.

CHAPTER 3

GENERAL PETROGRAPHY

The rocks studied were all basalts however there are some important petrographic differences between the North Mountain samples and those from the Mobil-Gulf Chinampas N-37 well.

Mineralogy

All the samples studied contain plagioclase, augite and magnetite as major mineral phases. Both plagioclase and augite occur as phenocrysts and microlites in the groundmass. Orthopyroxene was rarely observed forming the core of larger grains, the rims of which are clinopyroxene (Plate 1, Appendix A). Pigeonite is ubiquitous but not nearly as abundant as augite or sub-calcic augite and often forms the core of grains rimmed by augite. It also occurs as distinct crystals in the groundmass. Pigeonite is distinuished from augite in plane polarized light by slightly higher relief, a distinct fracture pattern and it tends to be more colourless. Magnetite occurs primarily in the groundmass closely associated with a brownish coloured to black devitrified glass.

Secondary minerals include a variety of zeolites (Aumento, 1965), magnetite, chlorite, and quartz (chalcedony, opal(?)). Apatite is a minor accessory mineral in the groundmass of some samples (Sinha, 1970). A red-brown stain common in many samples may be due to hematite. Olivine grains in some samples have been completely replaced by alteration products.

Zoned plagioclase phenocrysts have compositions of An 50-70; compositions of the groundmass plagioclase were not determined. The An content was determined optically using the Michel-Levy method method of maximum symmetrical extinction. Feldspar generally constitutes 30-45% of the rock. Roughly equivalent to plagioclase in modal abundance are the major pyroxenes, augite and sub-calcic augite. Pigeonite and orthopyroxene are much less abundant but demonstrate the tholeiitic character of the basalts. Magnetite makes up 2-8% of the North Mountain samples with a mean of 3-4 percent. The modal abundance of magnetite in the Mobil-Gulf samples is higher, being 10-15% of the rock.

Textures

All the rocks examined are porphyritic, with phenocrysts of both augite and plagioclase, and several samples are amygdaloidal. In the coarser grained varieties, plagioclase often exhibits oscillatory zoning and ophitic or sub-ophitic texture is common (Plate 2, Appendix A). In the finer grained varieties, magnetite and devitrified or altered glass show intersertal texture (Plate 3, Appendix A). All the samples contained devitrified, pigmented glass with the modal abundance of glass being higher in the finer grained rocks. Where the devitrified glass patches are black, the colour appears to be related to finely divided magnetite. Idiomorphic magnetite is preferentially found in or closely associated with the altered glass, and microlites of plagioclase or augite are rarely observed in these patches.

Where the rocks are extensively zeolitized, pseudomorphic textures are common. Relict olivine grains are observed in some samples.

Alteration

As a general rule, augite phenocrysts are unaltered whereas plagioclase ranges from unaltered to being extensively replaced by sericite , zeolites and clay minerals. In some samples there are euhedral brownish patches which are iddingsite and/or biotite pseudomorphs after olivine. Hematization is more extensive and pronounced in the Bay of Fundy samples, largely because noticeably oxidized material from North Mountain was not examined.

Amygdules are infilled with a variety of zeolites. The amygdules are commonly lined with quartz (chalcedony) and/or chlorite. The Mobil-Gulf samples are amygdaloidal as well but the vesicles have been infilled with chlorite, and calcite was rarely observed (Plate 3, Appendix A).

Augite phenocrysts are occasionally replaced by chlorite (Plate 4, Appendix A) but are generally unaltered, even where the rock is extensively altered (Plate 3, Appendix A). A light green to green mineral (mineraloid?) observed in some samples was not optically identified. In an attempt to resolve this problem, two of these green spots were analysed with the electron microprobe. The analyses are given in Table 3.

Table 3

	G-1	G-2
SiO_2	54.37	54.55
Al_2O_3	5.47	5.28
FeO	15.34	15.05
MgO	7.07	7.15
CaO	0.16	0.15
K_2O	9.80	9.74
	92.29%	91.92%

The poor totals are undoubtedly the result of high water content. The high potassium content rules out the possibility this mineral is chlorite.

CHAPTER 4

WHOLE ROCK GEOCHEMISTRY

All samples from the North Mountain drill hole (GAV-77-3) were analysed for major elements, minor elements and a variety of trace elements. Three of these samples were analysed for rare earth elements (REE). Because of the limited material from the Chinampas N-37 hole, only one sample was analysed for major and minor elements (MG-10) but several were analysed for trace elements. Analytical techniques are described in Appendix B.

Major Elements

Results of major element analyses on twelve (12) corehole samples from GAV-77-3 and one sample from the Mobil-Gulf core are given in Table 4. Sample locations are shown on Figures 2 and 3 respectively. In Table 4, the data are arranged in order of decreasing depth of the samples in the corehole and the volatile-free CIPW normative compositions ($Fe_2O_3/[Fe_2O_3+FeO]=0.15$) are also given. The samples were only analyzed once for each element therefore no precision data is available. U.S.G.S. rock standards AGV-1 and BCR-1 were analyzed simultaneously to provide some idea as to the reliability of the analyses. Limited sample availability of these standards did not allow the determination of H_2O^+,

H_2O^- or CO_2. These values were taken from Geological Survey of Canada Paper 72-30 and Geological Survey of Canada Paper 77-34.

Table 5 shows the analyses recalculated on a dry basis (H_2O^- omitted) so they may be compared to the most recent publication of "useable values" for standard samples (G.S.C. Paper 77-34).

Table 6 shows the major element analyses recalculated on a volatile-free basis. The reason for presenting Table 6 is to show that the samples meet the requirements necessary for using one of the discriminator diagrams to be presented in another section (Fig. 7).

Chemical evidence of variable alteration in the suite of North Mountain samples is reflected in the variable concentrations of some of the major element oxides. One measure of the degree of alteration is the ratio between the ferric and ferrous oxides ($\frac{Fe_2O_3}{FeO + Fe_2O_3}$) when these ratios are calculated, the values range from 0.19 to 0.45. The total water values are highly variable ranging from 2.07 to 7.27 percent. H_2O^+ values are somewhat less variable ranging from 1.52 to 5.61 percent. When the iron ratios are arranged from lowest to highest and the corresponding

MAJOR ELEMENT OXIDES AND NORMATIVE COMPOSITIONS

TABLE 4

	1-1	1-2	1-3	1-4	1-5	2-1	4-1	7-1	11-1	13-1	14-1	15-1	MG-10	AGV-1	BCR-1	N.M. AVER.	N.M. S
SiO_2	51.04	50.74	50.41	50.18	48.92	46.79	52.01	49.51	49.36	48.80	49.55	48.59	51.20	59.72	54.50	49.66	1.36
TiO_2	1.32	1.11	1.40	1.26	0.82	1.24	1.24	1.28	1.28	1.42	1.30	1.36	1.35	1.05	2.21	1.25	0.16
Al_2O_3	13.71	13.21	14.32	14.54	14.50	14.20	14.01	14.23	13.90	13.57	13.66	14.06	14.16	16.73	13.79	13.99	0.40
Fe_2O_3	2.50	2.42	1.98	3.48	3.34	3.17	3.32	4.43	4.09	3.84	3.87	4.78	2.51	4.30	3.31	3.44	0.48
FeO	7.63	7.48	8.52	6.66	7.02	6.84	6.89	6.41	6.45	6.74	6.37	5.79	6.55	2.25	8.95	6.90	0.71
MnO	0.20	0.19	0.18	0.17	0.17	0.27	0.24	0.17	0.17	0.18	0.17	0.17	0.20	0.10	0.19	0.19	0.03
MgO	7.01	7.81	5.73	6.02	6.90	6.52	6.54	5.77	6.24	5.87	5.79	6.16	7.21	1.56	3.39	6.36	0.63
CaO	10.57	10.88	10.16	9.74	10.45	9.16	9.22	9.29	9.41	9.15	9.32	9.19	5.48	4.80	7.14	9.71	0.63
Na_2O	1.96	1.88	2.27	2.15	2.16	2.92	3.33	2.90	2.70	2.76	2.83	2.59	5.10	4.26	3.26	2.54	0.45
K_2O	0.76	0.72	0.38	1.33	0.09	1.32	0.88	1.10	1.13	0.66	0.50	0.88	1.04	2.87	1.66	0.81	0.38
P_2O_5	0.12	0.12	0.18	0.14	0.14	0.14	0.13	0.14	0.33	0.14	0.13	0.14	0.14	0.45	0.36	0.15	0.06
H_2O+	1.79	1.52	1.60	2.13	3.31	5.45	2.05	3.72	3.49	5.42	5.61	5.02	3.84	0.60	0.72	4.15	1.42
H_2O^-	1.45	0.55	0.48	1.17	2.23	1.38	1.18	0.99	0.95	1.69	1.66	1.21	0.58	1.21	0.89	1.25	0.49
CO_2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.		
Totals	100.06	98.63	97.61	98.97	100.05	99.40	101.04	99.94	99.50	100.24	100.76	99.94	99.36	99.90	100.37	100.40	

.........Continued

Continued

MAJOR ELEMENT OXIDES AND NORMATIVE COMPOSITIONS

TABLE 4

	1-1	1-2	1-3	1-4	1-5	2-1	4-1	7-1	11-1	13-1	14-1	15-1	MG-10
Q	3.81	2.77	4.85	2.13	2.27	0.00	0.00	0.00	0.00	1.19	2.19	0.30	6.49
Or	4.65	4.41	2.35	8.24	0.56	8.48	5.33	6.85	7.05	4.20	3.17	5.57	-
Ab	17.14	16.48	20.12	19.05	19.38	26.84	28.86	25.84	24.10	25.14	25.68	23.47	45.04
An	27.26	26.41	29.07	27.33	31.38	23.62	21.18	23.76	23.70	24.42	24.77	25.85	13.37
Di	21.40	23.44	18.54	18.36	18.56	20.29	20.36	19.60	19.13	19.32	19.69	18.09	11.68
Hy	20.61	21.80	19.48	19.78	23.52	1.48	18.00	15.97	19.26	20.06	19.20	21.22	-
Ol	0.00	0.00	0.00	0.00	0.00	14.14	1.32	2.60	1.03	0.00	0.00	0.00	18.08
Mt	2.25	2.21	2.37	2.26	2.34	2.24	2.23	2.42	2.36	2.42	2.33	2.38	2.05
Il	2.59	2.19	2.78	2.51	1.65	2.56	2.41	2.56	2.56	2.90	2.65	2.77	2.70
Ap	0.29	0.29	0.44	0.34	0.34	0.35	0.31	0.34	0.81	0.35	0.32	0.35	0.34
Ne	-	-	-	-	-	-	-	-	-	-	-		0.25
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Notes

1. Fe_2O_3 = Total Fe as Fe_2O_3+ - FeO (1.1113) where FeO was determined by titration.
2. Fe_2O_3 normalized to $Fe_2O_3/(FeO + Fe_2O_3) = 0.15$ for CIPW norm calculations.
3. Sample GM-10 is from Chinampas N-37 hole in the Bay of Fundy.
4. n.d. - not detected.

MAJOR ELEMENT OXIDES

TABLE 5

H_2O^- Omitted (% dry basis)

	1-1	1-2	1-3	1-4	1-5	2-1	4-1	7-1	11-1	13-1	14-1	15-1	GM-10	AGV-1*	BCR-1*
SiO_2	51.79	51.02	50.66	50.78	50.04	47.45	52.62	50.01	49.83	49.63	50.38	49.19	51.50	59.72 59.72	54.85 54.50
TiO_2	1.34	1.12	1.41	1.28	0.84	1.26	1.25	1.29	1.29	1.44	1.32	1.38	1.36	1.05 1.06	2.22 2.22
Al_2O_3	13.91	13.28	14.39	14.71	14.83	14.40	14.18	14.37	14.03	13.80	13.89	14.23	14.24	17.22 16.95	13.68 13.86
Fe_2O_3	2.54	2.43	1.99	3.52	3.42	3.21	3.36	4.47	4.13	3.91	3.93	4.84	2.52	4.57 4.36	3.48 3.32
FeO	7.74	7.52	8.56	6.74	7.18	6.94	6.97	6.47	6.51	6.86	6.48	5.86	6.59	2.08 2.28	9.05 9.00
MnO	0.20	0.19	0.18	0.17	0.17	0.27	0.24	0.17	0.17	0.18	0.17	0.17	0.20	0.10 0.10	0.19 0.19
MgO	7.11	7.85	5.76	6.09	7.06	6.61	6.62	5.83	6.30	5.97	5.89	6.24	7.25	1.55 1.58	3.49 3.41
CaO	10.73	10.94	10.21	9.86	10.69	9.29	9.33	9.38	9.50	9.31	9.48	9.30	5.51	5.00 4.86	6.98 7.18
Na_2O	1.99	1.89	2.28	2.18	2.21	2.96	3.37	2.93	2.74	2.81	2.88	2.62	5.13	4.31 4.32	3.29 3.28
K_2O	0.77	0.72	0.38	1.35	0.09	1.34	0.89	1.11	1.14	0.67	0.51	0.89	1.05	2.93 2.91	1.68 1.67
P_2O_5	0.12	0.12	0.18	0.14	0.14	0.14	0.13	0.14	0.33	0.14	0.13	0.14	0.14	0.50 0.46	0.33 0.36
H_2O^+	1.82	1.53	1.61	2.16	3.39	5.53	2.07	3.76	3.52	5.51	5.70	5.08	3.86	0.82 0.61	0.73 0.72
Total	100.06	98.61	97.61	98.98	100.06	99.40	101.03	99.93	99.49	100.23	100 .76	99.94	99.35	99.21	99.71

*Upper values are those reported as "usable" in GSC Paper 77-34 .

Lower values are those obtained by the analyst.

MAJOR ELEMENT OXIDES
VOLATILE FREE

TABLE 6

	1-1	1-2	1-3	1-4	1-5	2-1	4-1	7-1	11-1	13-1	14-1	15-1	MG-10	AGV-1	BCR-1
SiO_2	52.75	51.83	51.51	51.91	51.79	50.24	53.73	51.96	51.67	52.53	53.40	51.82	53.58	60.45	54.99
TiO_2	1.36	1.13	1.43	1.30	0.87	1.33	1.28	1.34	1.34	1.53	1.40	1.45	1.41	1.06	2.23
Al_2O_3	14.17	13.49	14.63	15.04	15.35	15.25	14.47	14.93	14.55	14.61	14.72	14.99	14.82	16.94	13.91
Fe_2O_3	2.58	2.47	2.02	3.60	3.54	3.40	3.43	4.65	4.28	4.13	4.17	5.10	2.63	4.35	3.34
FeO	7.89	7.64	8.71	6.89	7.43	7.34	7.12	6.73	6.75	7.25	6.87	6.17	6.85	2.28	9.03
MnO	0.21	0.19	0.18	0.18	0.18	0.29	0.25	0.18	0.18	0.19	0.18	0.18	0.21	0.10	0.19
MgO	7.24	7.98	5.85	6.23	7.30	7.00	6.76	6.06	6.53	6.32	6.24	6.57	7.55	1.58	3.42
CaO	10.92	11.11	10.38	10.08	11.06	9.84	9.52	9.75	9.85	9.85	10.04	9.80	5.74	4.86	7.20
Na_2O	2.03	1.92	2.32	2.22	2.29	3.14	3.44	3.04	2.83	2.97	3.05	2.76	5.34	4.31	3.29
K_2O	0.79	0.74	0.39	1.38	0.10	1.42	0.91	1.15	1.18	0.71	0.54	0.94	1.09	2.91	1.67
P_2O_5	0.12	0.12	0.18	0.14	0.15	0.15	0.13	0.15	0.35	0.15	0.14	0.15	0.15	0.46	0.36
Total	100.06	98.62	97.60	98.97	100.06	99.40	101.04	99.94	99.51	99.94	100 .75	99.93	99.37	99.30	99.63

H_2O^+ values are listed, some interesting observations can be made (Table 7).

TABLE 7

Sample	$Fe_2O_3/(FeO + Fe_2O_3)$	H_2O^+
1-3	0.19	1.60
1-2	0.24	1.52
1-1	0.25	1.79
MG-10	0.28	3.84
1-5*	0.32	3.31
2-1*	0.32	5.45
4-1*	0.33	2.05
1-4*	0.34	2.13
13-1*	0.36	5.42
14-1	0.38	5.61
11-1*	0.39	3.49
7-1*	0.41	3.72
15-1*	0.45	5.02

Notes

1. * is any sample described as amygdaloidal.
2. No petrographic information for sample MG-10.

From Table 7 it can be seen that high water content corresponds to the presence of zeolites. It is reasonable to expect this since the zeolites incorporate water in their crystal lattice (Deer, Howie and Zussman, 1975). Samples 1-1, 1-2 and 1-3 which are massive contain the least amount of water and have the lowest $Fe_2O_3/(FeO + Fe_2O_3)$ ratios. There is a rough correlation (correlation coefficient = 0.65) between the iron ratios and H_2O^+ (Fig. 5). Sample 4-1 is somewhat anomalous in that it is amygdaloidal but has one of the lowest water contents.

The K_2O content is highly variable, ranging from 0.09 - 1.33 percent. This is a range not expected in a relatively thin sequence of 16 flow units. The range of K_2O values in individual tholeiitic basalts worldwide is quite large, ranging from approximately 0.01 to 2.6 weight percent (Manson, 1967). The distribution of K_2O in the average analyses of tholeiitic provinces is very similar to the distribution in individual basalts but the total range (0.07-1.61 percent) is more restricted (Jamieson and Clarke, 1970). Weigand and Ragland (1970) have established four chemical types of Eastern North American (ENA) dolerites which are similar to many other basalts in general regard but they state there are minor specific differences which establish the ENA dolerites as a distinct geochemical basalt province. The North Mountain Basalt belongs to the ENA basalt province (Bertrand and Coffrant, 1977) and should therefore not exhibit a range of K_2O values which

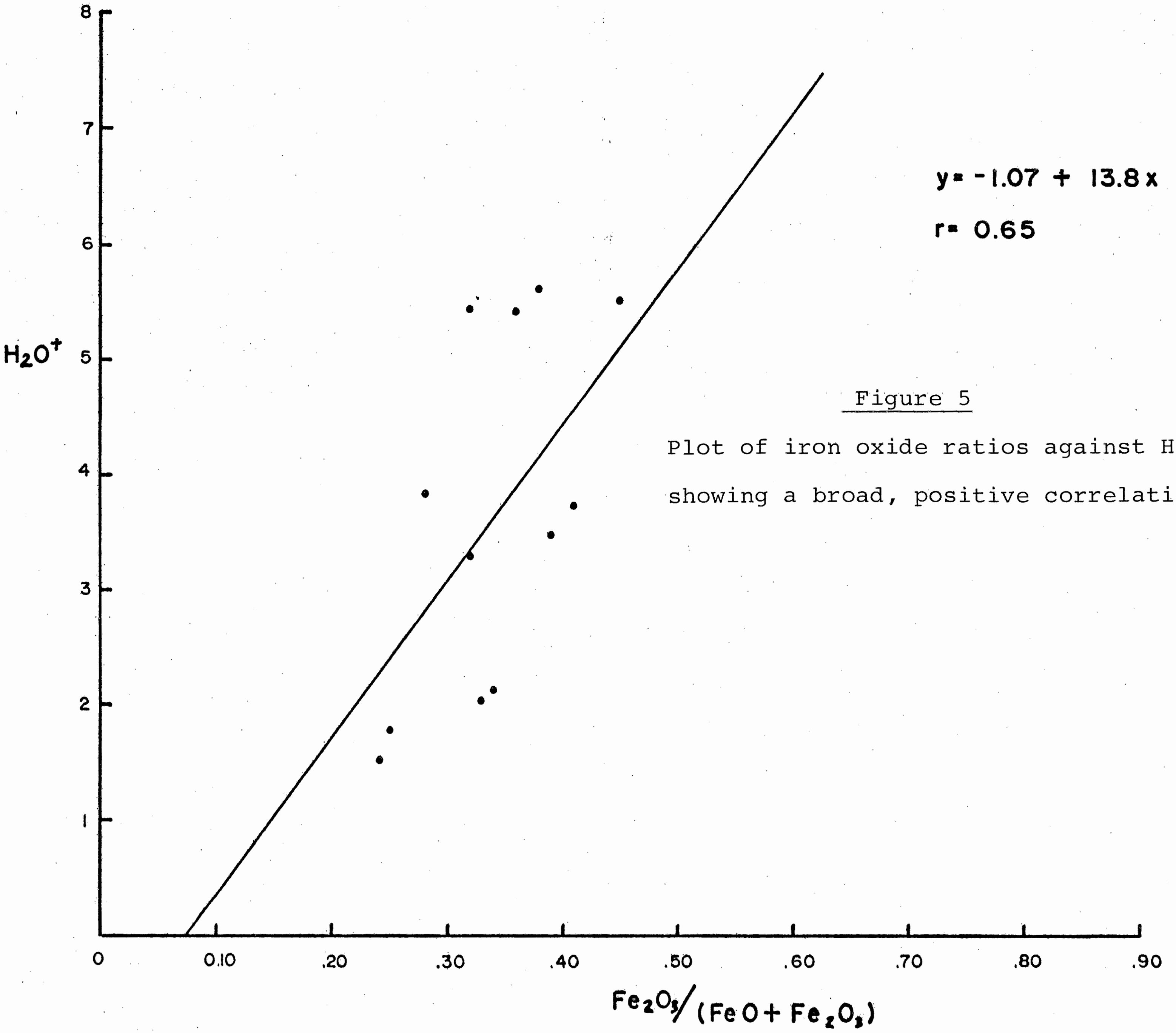

Figure 5

Plot of iron oxide ratios against H_2O+ showing a broad, positive correlation.

is nearly equivalent to the range for average analyses of tholeiitic provinces worldwide. An explanation for the erratic concentration of K_2O will be presented in another section.

The MgO values range from 5.73-7.81% with the highest and lowest concentrations being found in the thick lowermost flow. This is similar to K_2O insofar as both the highest and lowest concentrations of this oxide are also in the lowermost flow. Samples containing relict olivine curiously do not have the highest MgO contents. The high MgO contents are found in the least altered samples and may be due to the presence of unaltered clinopyroxenes. The Mobil-Gulf sample (MG-10) has high MgO but this is probably due to abundant chlorite. There is no systematic decrease in MgO content from the base of the North Mountain basalts to the top of the lava pile.

The Na_2O content ranges from 1.88-3.33% with the lowest concentrations being in the lowermost flow. The CaO values range from 9.15-10.88% with the samples from the lowest flow being slightly higher than the remaining flows. Sample 1-2 has the highest CaO content and lowest Na_2O content. Sample 1-1 has the second highest CaO content and second lowest Na_2O content. These samples are both massive and may be a result of small scale feldspar differentiation in the bottom flow.

One important feature of these samples is the relatively uniform concentration of two minor constituents, phosphorus and titanium. P_2O_5 concentrations are virtually the same ranging from 0.12 to 0.14% with two exceptions. Sample 1-3 has a concentration of 0.18 percent and 11-1 has a concentration of 0.33 percent. Titanium is not as uniformly distributed as phosphorus, ranging from 1.11-1.36 percent. Sample 1-5 has a noticeably low TiO_2 concentration (0.82%). This low value appears to correlate with low SiO_2 and K_2O and with a relatively high H_2O content.

It is important that phosphorus and titanium do not show wide variation as these are two of the elements considered to be tectonic environment discriminators. These data also reinforce the conclusions of previous studies of mafic rocks (Cann, 1970; Pearce and Cann, 1971, 1973: Pearce et al., 1975; Floyd and Winchester, 1975; Winchester and Floyd, 1976) where it has been shown that Ti and P as well as the trace elements Y, Zr and Nb remain relatively immobile through processes such as weathering, deuteric alteration and greenschist facies metamorphism.

Total iron concentrations show relatively small variation ranging from 9.90-10.84 percent.

The major element chemistry of sample MG-10 is similar to the North Mountain samples but there are some noteable differences. The total iron content (FeO + Fe_2O_3) is 9.06% compared to 9.90% for sample 1-2 which has the lowest total iron content of the North Mountain samples. The sodium and calcium concentrations are significantly different. CaO is low with respect to the North Mountain samples while Na_2O is higher. This chemical pattern is characteristic of spilites and it is suggested that this sample may be spilitized. There is some petrographic evidence from other Mobil-Gulf samples which support this. Amygdules in the Mobil-Gulf samples are largely infilled with chlorite, and calcite was occasionally observed. The feldspars are extensively sericitized and kaolinized with some suggestion of albitization.

Normative Composition

Figure 6 is a plot of the CIPW normative compositions of the basalts after Toder and Tilley (1962). The values were computed on a water-free basis using the CIPW normative program and $Fe_2O_3/(FeO + Fe_2O_3)$ ratios were normalized to 0.15 prior to entering the data (Table 4). On the basis of their normative mineralogy, all the North Mountain basalts plot in the tholeiitic

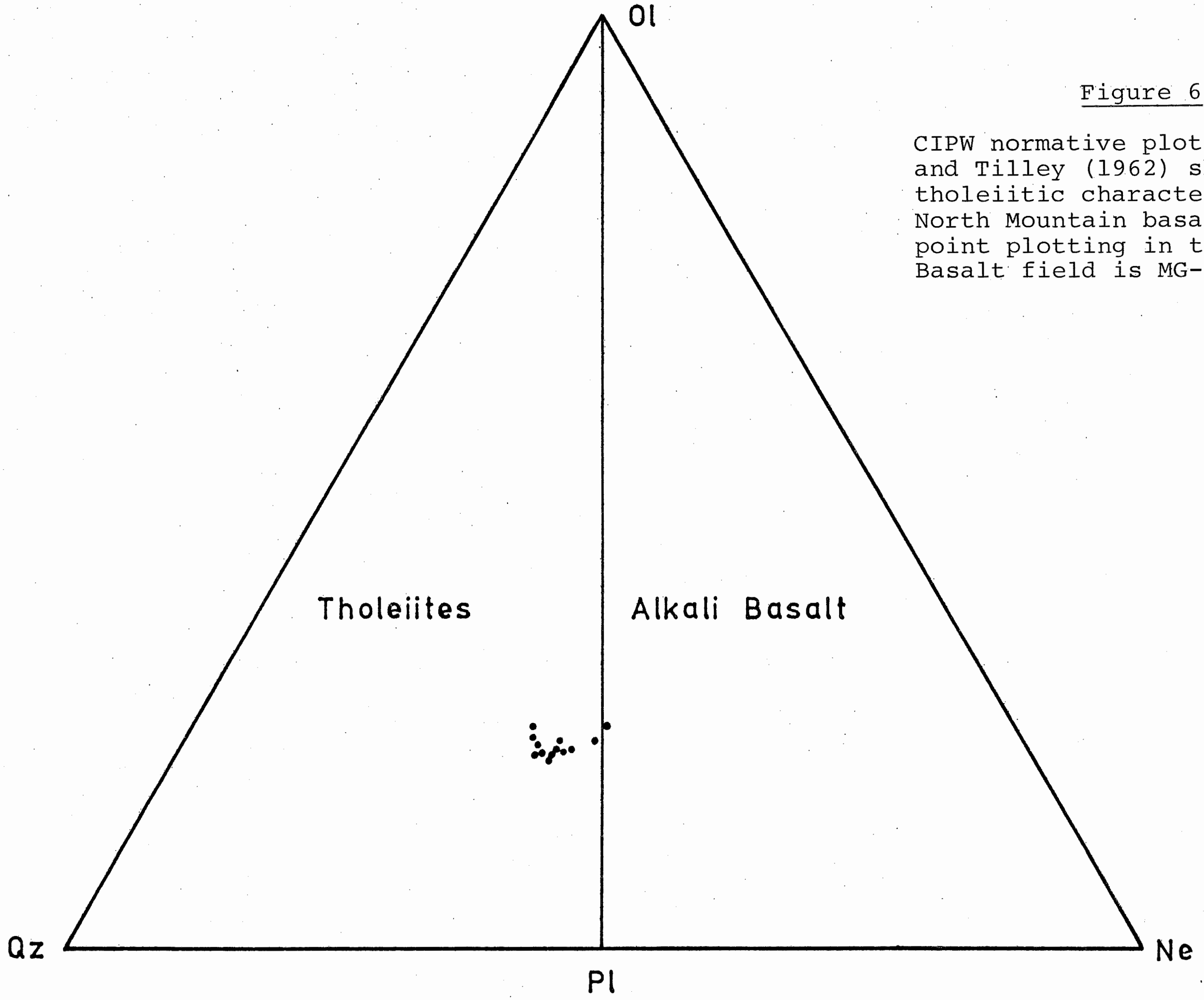

Figure 6

CIPW normative plot after Yoder and Tilley (1962) showing the tholeiitic character of the North Mountain basalts. The point plotting in the Alkali Basalt field is MG-10.

field whereas MG-10 plots as an alkali basalt just outside the tholeiitic field. This is probably a result of the irregular Na_2O and CaO concentrations previously noted.

The North Mountain samples all plot in a tight group with the exception of 2-1 which plots very close to the olivine-plagioclase join. The tight clustering of both altered and fresh samples may suggest that post-eruptive processes such as weathering, hydrothermal alteration and metamorphism have not had a significant effect in altering the bulk composition of the rocks.

All tholeiitic basalts have normative hypersthene and normative quartz is typical of tholeiitic basalts poor in, or lacking, modal olivine (Carmichael *et al.*, 1974). The North Mountain basalts are all hypersthene-normative and all but four are quartz-normative (Table 4). The normative mineralogy is consistent with the hypersthene bearing modal character of the rocks. Samples lacking normative quartz contain normative olivine. Samples containing normative quartz and hypersthene are oversaturated tholeiites while those containing normative hypersthene and olivine are undersaturated olivine tholeiites (Wilkinson, 1967).

Trace Elements

Results of analyses for twenty-two (22) trace

TABLE 8

TRACE ELEMENT CONCENTRATIONS (ppm) IN NORTH MOUNTAIN AND GULF-MOBIL SAMPLES

	1-1	1-2	1-3*	1-4	1-5*	2-1	4-1	7-1*	11-1	13-1	14-1	15-1	MG-4	MG-5	MG-7	MG-11	AGV-1	AGV-1	BCR-1
Ba	179	174	202	216	119	186	190	234	244	232	175	265	155	156	288	185	1218	1218	740
Cr	149	252	76	83	93	116	132	101	164	91	88	83	172	92	127	318	12	12	25
Cu	225	130	138	103	430	102	275	91	54	57	100	120	90	71	127	99	64	64	28
Ga	21	17	26	20	22	19	22	20	22	21	22	14	21	23	20	23	23	23	22
Nb	7	6	12	11	9	12	9	10	12	12	10	7	9	10	10	9	12	12	12
Ni	59	82	51	53	58	59	58	51	52	54	51	44	70	48	54	89	13	13	11
Rb	16	14	22	18	5	28	19	23	39	14	18	16	27	21	22	20	70	70	49
Sr	203	175	194	182	192	259	145	184	165	208	197	218	195	109	208	171	687	687	338
V	241	247	265	264	267	260	280	267	285	249	253	255	256	280	281	249	129	129	402
Y	19	18	19	18	17	19	19	20	23	20	19	18	21	20	20	19	22	22	36
Zn	79	70	87	73	81	132	96	71	78	84	81	68	83	74	81	83	87	87	121
Zr	109	100	124	118	118	117	109	117	112	128	111	114	112	114	117	101	233	233	188

........Continued/

TABLE 8 (continued)

RARE EARTH ELEMENTS

	1-1	1-2	1-3*	1-4	1-5*	2-1	4-1	7-1*	11-1	13-1	14-1	15-1	MG-4	MG-5	MG-7	MG-11	AGV-1	AGV-1	BCR-1
La	-	-	12.64	-	12.23	-	-	12.32	-	-	-	-	-	-	-	-	34.70	35.30	27.39
Ce	-	-	26.13	-	24.04	-	-	27.12	-	-	-	-	-	-	-	-	63.14	62.86	64.87
Nd	-	-		-		-	-		-	-	-	-	-	-	-	-	41.13	37.08	41.41
Sm	-	-	3.85	-	3.64	-	-	3.88	-	-	-	-	-	-	-	-	6.00	5.81	7.83
Eu	-	-	1.35	-	1.30	-	-	1.28	-	-	-	-	-	-	-	-	1.68	1.72	2.51
Tb	-	-	0.60	-	0.75	-	-	0.62	-	-	-	-	-	-	-	-	0.69	0.71	1.05
Yb	-	-	2.23	-	1.98	-	-	2.27	-	-	-	-	-	-	-	-	1.83	1.59	3.83
Lu	-	-	0.43	-	0.34	-	-	0.32	-	-	-	-	-	-	-	-	0.28	0.28	0.55

Notes:

1. R.E.E. values for samples 1-3, 1-5, 7-1, AGV-1 and BCR-1 determined at Dalhousie University using I.N.A.A.
2. All other trace element values determined by XRF at Memorial University.

TABLE 9 MEAN AND STANDARD DEVIATION VALUES FOR THE NORTH MOUNTAIN AND MOBIL-GULF BASALTS

ELEMENT	NORTH MOUNTAIN		MOBIL-GULF	
	$\overline{X}$	S	$\overline{X}$	S
Ba	201.3	39.5	196	62.9
Cr	119	50.4	205.4	106.6
Cu	152.1	96.8	108.5	23.3
Ga	20.5	3.0	21.8	1.5
Nb	9.5	9.5	2.2	0.6
Ni	56	9.3	65.3	18.4
Rb	19.3	8.4	22.5	3.1
Sr	193.5	28.5	170.8	43.9
V	261.6	13.5	266.5	16.4
Y	19.1	1.4	20	0.8
Zn	83.3	17.2	80.3	4.3
Zr	114.7	7.1	111	7.0

Note: All values are ppm

TABLE 10 SELECTED ELEMENTS FROM NORTH MOUNTAIN SAMPLES GROUPED CHEMICALLY (Modified after Gottfried *et al.*,1977)

	1-1	1-2	1-3	1-4	1-5	2-1	4-1	7-1	11-1	13-1	14-1	15-1
						LARGE CATIONS						
Rb^+	16	14	22	18	5	28	19	23	39	14	18	16
Ba^{+2}	179	174	202	216	119	186	190	234	244	232	175	265
K^+	6,300	6,000	3,200	11,000	700	11,000	7,300	9,100	9,400	5,500	4,200	7,300
Sr^{+2}	203	175	194	182	192	259	145	184	165	208	197	218
Ca^{+2}	75,500	77,800	72,600	69,600	74,700	65,500	65,900	66,400	67,300	65,400	66,600	65,700
K/Rb	394	429	145	611	140	393	384	396	241	393	233	456
Ba/Rb	11	12	9	12	24	7	10	10	6	17	10	17
K/Ba	35	34	16	51	6	59	38	39	39	24	24	28
						HIGH VALENCE CATIONS						
Zr^{+4}	109	100	124	118	118	117	109	117	112	128	111	114
Nb^{+5}	7	6	12	11	9	12	9	10	12	12	10	7

.......Continued/

TABLE 10 (Continued)

TRANSITION ELEMENTS (and Ga)

	1-1	1-2	1-3	1-4	1-5	2-1	4-1	7-1	11-1	13-1	14-1	15-1
Cu^{+2}	225	130	138	103	430	102	275	91	54	57	100	120
Ni^{+2}	59	82	51	53	58	59	58	51	52	54	51	44
Zn^{+2}	79	70	87	73	81	132	96	71	78	84	81	68
Cr^{+3}	149	252	76	83	93	116	132	101	164	91	88	83
V^{+3}	241	247	265	264	267	260	280	267	285	249	253	255
Ga^{+3}	21	17	26	20	22	19	22	20	22	21	22	14

Note: All concentrations in ppm

elements in individual samples are reported in Table 8 . The mean values and standard deviations are given in Table 9 . Since most of the commonly employed discriminant diagrams are based on minor or trace elements, it is important to evaluate the effects of post-eruptive alteration in the basalts. The data have been rearranged (Table 10) and modified after Gottfried *et al*. (1977) to facilitate the following discussion by comparing elements with similar chemical behaviour.

Large Cations

The large cations, Rb, Ba and K do not easily fit into the crystal structures of the major minerals of basaltic rocks and are therefore most probably concentrated in interstitial material such as glass. Because of this, they may be more susceptible to leaching and remobilization by geologic processes during and after crystallization (Gottfried *et al*., 1977).

The irregular distribution of K_2O was previously discussed and it is probable that the pattern is due to post-eruptive alteration by hydrothermal fluids. Rubidium and barium do not appear to have a regular distribution pattern but since they behave chemically like potassium, a positive correlation coefficient would be expected between potassium and these elements if their distribution is also affected by hydrothermal fluids. Correlation coefficients for these and other 'incompatible elements' are presented in Table 11.

Table 11

Correlation coefficients for the 'incompatible' elements (after Jamieson and Clarke, 1970).

	K_2O	P_2O_5	TiO_2	Ba	Rb	Sr	Zr
K_2O	-	0.20	0.36	0.57	0.64	-0.03	-0.11
P_2O_5	0.20	-	0.12	0.38	0.76	-0.26	0.08
TiO_2	0.36	0.12	-	0.74	0.43	0.22	-0.29
Ba	0.57	0.38	0.74	-	0.51	0.01	0.24
Rb	0.64	0.76	0.43	0.51	-	-0.03	-0.02
Sr	-0.03	-0.26	0.22	0.01	-0.03	-	0.36
Zr	-0.11	0.08	-0.29	0.24	-0.02	0.36	-

From Table 11 it is seen that there is a moderately good positive correlation between potassium and rubidium as well as potassium and barium. These observations are similar to those reported by Gottfried et al. (1977) in their study of corehole basalt from South Carolina. In general, there is normally a good correlation between these elements in basaltic rocks (Jamieson and Clarke, 1970). One of the best correlations is that between

K_2O and Rb and Gottfried et al. (1977) have suggested that Rb is the most sensitive indicator of alteration and may be useful for subdividing heterogeneously altered flows into alteration domains. It is difficult to assess the usefulness of Rb as an alteration zone indicator for the North Mountain since obviously altered regions were not sampled, but, the levels are generally higher near the base of flows and may be lower near the oxidized flow tops. It is fully appreciated that the number of samples involved in this study may not be statistically significant, therefore only generalizations can be made. A more detailed interflow variation of major, minor and trace elements in the North Mountain Basalt is being studied by others and a publication may be forthcoming (Colwell, personal communication, 1980). It is interesting that the lowest Rb and Ba concentrations occur in sample 1-5. This sample is noticeably lower in K_2O and TiO_2 as well.

Because of the wide variation observed in potassium, rubidium and barium, the K/Rb and K/Ba ratios show wide variation (Table 10). Prinz (1967) reports an average K/Rb ratio of 349 for quartz-normative basalts. This compares quite well with the average of 351 for the North Mountain samples but this is purely coincidental since the K/Rb range is 140-611. This is a range far outside what would be normal for a suite of fresh basalts and probably means both K and Rb have been mobile since the rocks were formed.

The range of variation of Sr is less than that of K and Rb and is approximately equivalent to that of Ba (~ 3X), although it shows no correlation with any of these elements (Table 11). In fact, Sr shows no appreciable correlation with the other 'incompatable' elements. The strongest correlation (0.36) is with Zr. This may mean that while Ba, Rb and K have been mobile, Sr has remained relatively stable. Pearce and Cann (1973) have suggested that Sr may be useful as a discriminating element and these data seem to support their findings.

Pb concentrations were determined by X.R.F. but the values were too close to the detection limit to be meaningful.

High Valence Cations

The Zr and Nb contents are quite uniform for both the North Mountain and Mobil-Gulf samples. Zr ranges from 100-128 ppm (~ 0.3X) and Nb ranges from 6-12 ppm (2X). The small variation in the Zr content is good as it is used as a discriminant element. Nb has been considered to be a discriminant element as well (Pearce and Cann, 1973; Floyd and Winchester, 1975), but the twofold variation observed in these analyses may indicate that it has been somewhat remobilized, and its usefulness therefore reduced. From Table B-1 (Appendix B) it is seen that the precision for Nb is high but the accuracy is low. Zr has both high precision and accuracy.

Rare-Earth Elements

The rare earth elements are one of the most important groups of trace elements in studies dealing with tectonic setting of basic rocks (Frey *et al.*, 1968; Jakěs and Gill, 1970; Schilling, 1971; Jakěs and White, 1972). The rare-earth element abundances (Table 8) are virtually the same in the samples analysed. That sample 1-5 which appears to be the most altered on the basis of its major and trace elements, yet still has REE concentrations similar to the unaltered basalts will be discussed in another section.

The REE abundances were normalized to chondritic values using the values of Frey *et al.* (1968). The normalized abundances were plotted on semi-log paper against the REE atomic number (Fig. 12). Yttrium is sometimes plotted on these diagrams as it behaves chemically like the rare-earth elements. Y was not plotted on Fig. 12 because the concentrations were determined by XRF techniques and the REE values were determined by neutron activation. This makes the points on Fig. 12 consistent by using only one chemical technique.

Transition Elements

Chromium and Nickel

Some of the transition elements, in particular, chromium and nickel, are qualitatively useful as a measure of differentiation in basic rocks. Both these elements are removed at an early stage of differentiation in spinel, clinopyroxene and olivine. The Cr content of the North Mountain samples varies from 76-252 ppm. with a mean of 119 ppm. The Mobil-Gulf samples vary from 92-318 with a mean of 205 ppm. (Tables 8 and 9). The mean value for quartz-normative tholeiites reported by Prinz (1967) is 153 ppm. The North Mountain average is somewhat lower than this and the Mobil-Gulf average is somewhat higher. The Ni content of the North Mountain samples ranges from 44-82 ppm with a mean of 56 ppm. The Mobil-Gulf samples range from 48-89 ppm. with a mean of 65. The average value for quartz-normative tholeiites is 76 ppm. (Prinz, 1967).

The only generalization which can be made on the basis of the limited number of samples analysed is that the highest concentrations of both Cr and Ni in the North Mountain occur in the thick bottom flow. Since only four samples from the Chinampas N-37 well were analysed, the mean values may be somewhat misleading.

Copper

The Cu content of the North Mountain is highly variable, ranging from 54 to 430 ppm. with a mean of 152 ppm. The Mobil-Gulf samples show less extreme variation (71-127 ppm.) and have a mean of 97 ppm. The average value for quartz-normative tholeiites is 141 ppm. (Prinz, 1967). Copper is generally enriched in the residual liquids during tholeiitic differentiation (Gottfried et al., 1977) and is distributed in all the minerals of basaltic rocks including sulphides (Prinz, 1967). Because of these characteristics, it is difficult to account for the relatively high Cu content of the North Mountain basalts. Vilks (1978), in his study of the North Mountain suggested that Cu and Ti contents are higher in amygdaloidal rocks. The data from this study generally do not support this. The highest Cu concentrations occur in sample 1-5 which is the most altered but is not highly amygdaloidal. This sample also has the lowest Ti content. Sample 4-1 which is amygdaloidal has a high Cu content (275 ppm.) but the third lowest Ti concentration. The third highest Cu content (225 ppm.)occurs in massive, aphanitic rock (sample 1-1).

Vanadium

Vanadium values for both the North Mountain and Mobil-Gulf samples are fairly uniform with a range of 241-285 ppm. Prinz (1967) gives a mean of 266 ppm. for quartz-normative tholeiites. This compares quite well with a mean of 262 ppm. for North Mountain and 267 ppm. for the Mobil-Gulf samples.

Zinc

Zinc values range from 68-132 ppm. in the North Mountain samples and 74-83 ppm in the Mobil-Gulf samples. No statistical data was compiled by Prinz (1967) concerning zinc distribution in basalts.

Yttrium

Yttrium values are nearly constant, ranging from 17-23 ppm. The range is actually smaller than this (17-20 ppm.) if sample 11-1 is omitted. The high Y value in 11-1 may be analytical error. The other possibility is that the 'high' Y (23 ppm.) is real, as it appears to correlate with high Ba, Rb and V.

The nearly constant Y values, coupled with the high accuracy and precision data, suggests this element may be plotted on discriminant diagrams with confidence.

Gallium

Although Ga is not a transition element, it is discussed here for simplicity. Gallium has a narrow dispersion range and average values for most rock types are similar (Prinz , 1967). As a result of this, Ga appears to have little use as a 'fingerprinting' element. Prinz (1967) reports a mean of 21 ppm. for quartz tholeiites. The range for North Mountain is 14-26 ppm. with a mean of 21 ppm. The Mobil-Gulf samples range from 20-23 with a mean of 22 ppm.

Comparison of GAV-77-3 and Mobil-Gulf Samples

It is not immediately apparent from major element chemistry that the North Mountain and Mobil-Gulf basalts are chemically equivalent. When trace element concentrations are compared (Tables 8,9) these basalts appear to be chemically equivalent and correlation of the two is probable. For every trace element, these basalts are not statistically different at the first standard deviation level and in fact, the mean values are nearly the same for both. This suggests that the Mobil-Gulf basalts are the equivalent of the North Mountain tholeiites and might possibly be the submarine extension of North Mountain.

CHAPTER 5

MINERAL CHEMISTRY

Petrography of the North Mountain basalts and the Mobil-Gulf samples shows the feldspars range from relatively fresh to being completely replaced by alteration products. The important thing about these basalts is that the clinopyroxenes are largely unaltered or only slightly altered.

Nisbet and Pearce (1977) have proposed a tectonic environment discriminant diagram based on the analyses of 'fresh' clinopyroxene grains in mafic lavas. Their study was restricted to calcic clinopyroxenes (augite) and they report that either phenocrysts or groundmass grains may be used. Their results indicate that on the basis of clinopyroxene mineralogy, four environments can be distinguished. These are: 1) ocean floor basalts (OFB), 2) volcanic arc basalts erupted above subduction zones in island arcs or at active continental margins (VAB), 3) tholeiitic basalts erupted within plates in oceanic islands or continental rifts (WPT), and 4) alkalic basalts erupted within plates (WPA).

A total of 147 'augitic' clinopyroxene grains were analysed with the electron microprobe. The analyses included both phenocrysts and groundmass grains. A presentation of the results of these analyses as tables would be too voluminous, therefore the original computer printouts of the data are archived in an accompanying envelope*. Samples from both North Mountain and the Mobil-Gulf well were analysed.

Sample Heterogenity

No problems were encountered when the North Mountain samples were analysed since polished thin sections were cut from the same rock as the petrographic thin sections. There was no doubt about sample location. Some difficulty was encountered with the Mobil-Gulf samples due to the nature of the samples recovered. These samples consisted of broken rock fragments. Although samples were collected every ten feet (3.0 m.), the exact location of any given rock fragment is uncertain. Several hand-picked basalt fragments from the intervals sampled (Fig. 3) were mounted in epoxy discs and polished. An attempt to determine the heterogeneity of these samples was made by analysing clinopyroxene grains from different rock fragments. Results of these analyses are discussed elsewhere.

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* The accompanying envelope is attached to the copy of this thesis retained by the Science Library at Dalhousie University and is available on request.

CHAPTER 6

DISCUSSION

Introduction

Numerous sills, dikes and lava flows of Triassic-Jurassic age and tholeiitic affinity occur along the eastern margin of North America. These volcanics are associated with elongated basins filled with Triassic continental sediments (Bertrand and Coffrant, 1977). Weigand and Ragland (1970) have analysed over 100 Mesozoic dolerite dikes from eastern North America and have shown they are not chemically homogeneous from North to South; quartz-normative tholeiites predominate in the North whereas olivine-normative tholeiites are prevalent in the South. This study is not concerned with the North-South variation of these tholeiites, but rather with the paleotectonic environment of eruption of one particular suite of these ENA tholeiites, using whole rock and mineral geochemistry.

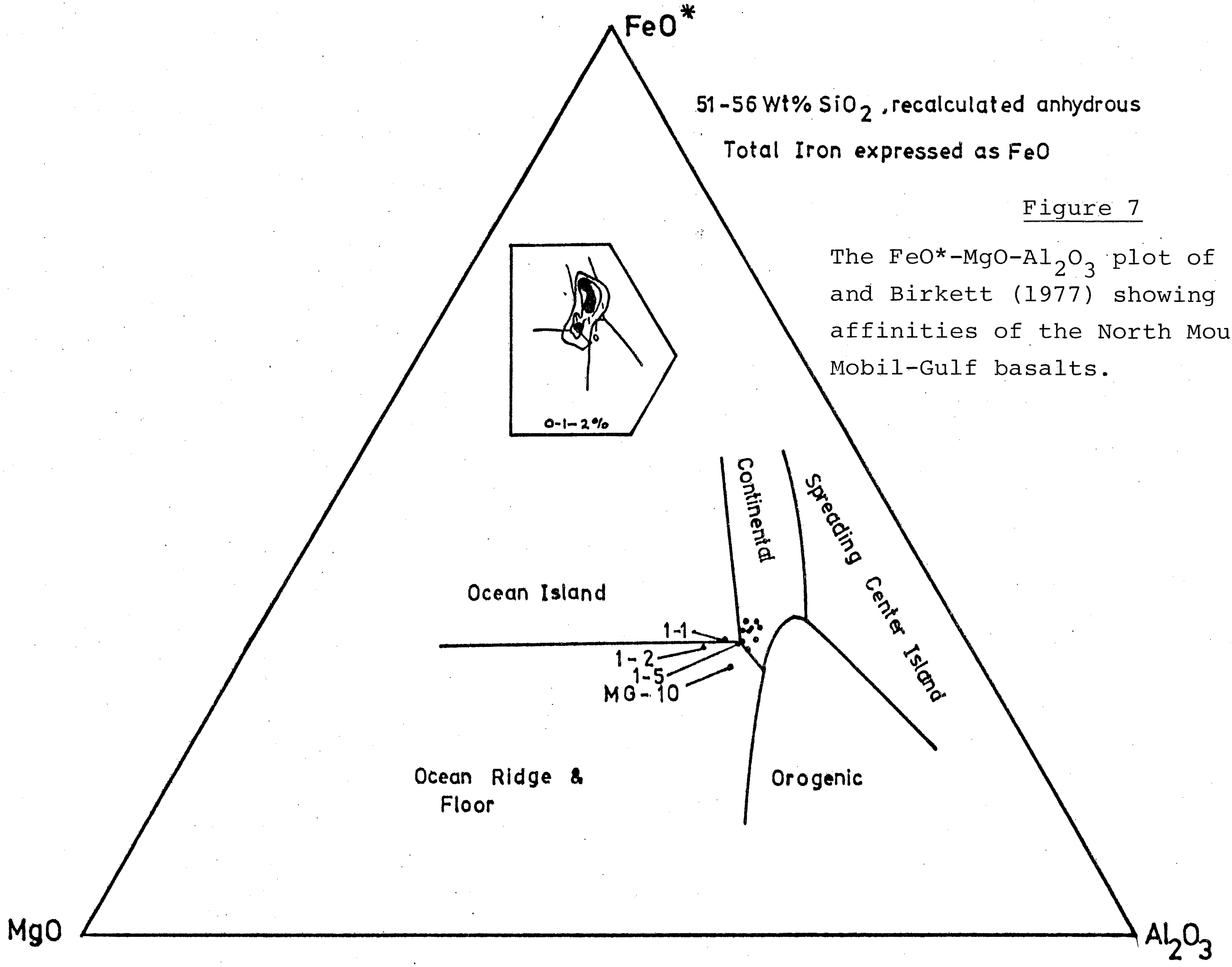
The chemical data previously presented have been plotted on various discriminant diagrams. The results have been sub-divided into four categories; Major Elements, Trace Elements, Rare Earth Elements, and Mineral Analyses.

Major Elements

Major element data and norms (Tables 4-6) show the North Mountain basalts are quartz-normative tholeiites with the exception of four samples which are olivine-normative. On the basis of normative mineralogy, the the solitary Mobil-Gulf sample plots as an alkalic basalt and is nepheline-normative. Possible reasons for this have been previously mentioned. The fact that these basalts are tholeiitic has no special significance in determining environment of eruption in terms of the various discriminating techniques (Pearce and Cann, 1973).

Figure 7 is a ternary plot of FeO*-MgO-Al_2O_3 after Pearce Gorman and Birkett (1977). This diagram shows that all but four samples plot in the region contoured as continental (inset diagram). In determining the boundaries of the various fields, analyses were restricted to rocks with 51-56 wt. % SiO_2 calculated anhydrous and the North Mountain basalts (Table 6) fit this constraint.

Samples 1-2, 1-5 and MG-10 which plot in the ocean ridge and floor field, and 1-1 which plots just inside the ocean island field have the highest MgO contents and consequently tend toward the MgO apex of the diagram.



<u>Figure 7</u>

The FeO*-MgO-Al_2O_3 plot of Pearce, Gorman and Birkett (1977) showing the tectonic affinities of the North Mountain and Mobil-Gulf basalts.

It is noteworthy that 1-5, which is the most altered sample, plots just outside of the continental field while 1-1 and 1-2 which are among the 'freshest' samples plot well inside the ocean ridge and floor field. The high Na_2O content of sample MG-10 suggests spilitization and the point plotted probably does not reflect the original chemistry of the rock.

Pearce *et al*. (1977) found that when their data points to delineate the continental field were contoured, two distinct modes appeared (inset diagram on Fig.7). They attributed this to age differences in the samples. The continental mode comprises rocks of predominantly post-Jurassic age. The "oceanic" mode consists of rocks of Triassic and Jurassic age. The North Mountain basalts cluster in the region contoured as Triassic-Jurassic continental and this is in accordance with the K-Ar age dates. In spite of the bimodality, the continental field was the most effective of all when classifying rocks on this diagram (Table 12).

Table 12

	Effectiveness of discriminant diagram for Cenozoic rocks
Ocean Ridge and floor	76%
Ocean Island	77%
Orogenic	66%
Continental	82%
Spreading Centre Island	64%

Pearce *et al*. (1977) used rocks of mainly Cenozoic age when defining the boundaries of Figure 7 , but state there is no reason why this technique cannot be extended to rocks older than Cenozoic. They also related the bimodal age/chemistry relationship of the continental rocks to the breaking up of continents and the timing of volcanism. They state (p.130), "During the active breaking up of a continent, it appears that flood basalts of a somewhat oceanic character are erupted. The Triassic and Jurassic basalts of worldwide distribution are examples of this type of volcanism".

The TiO_2-K_2O-P_2O_5 plot (Fig. 8) of Pearce *et al*. (1975), shows that most of the basalts plot in the continental field. Of the five samples from the lowermost flow, 1-1,1-2, and 1-4 plot in the continental field whereas 1-3 and 1-5 plot in the oceanic field.

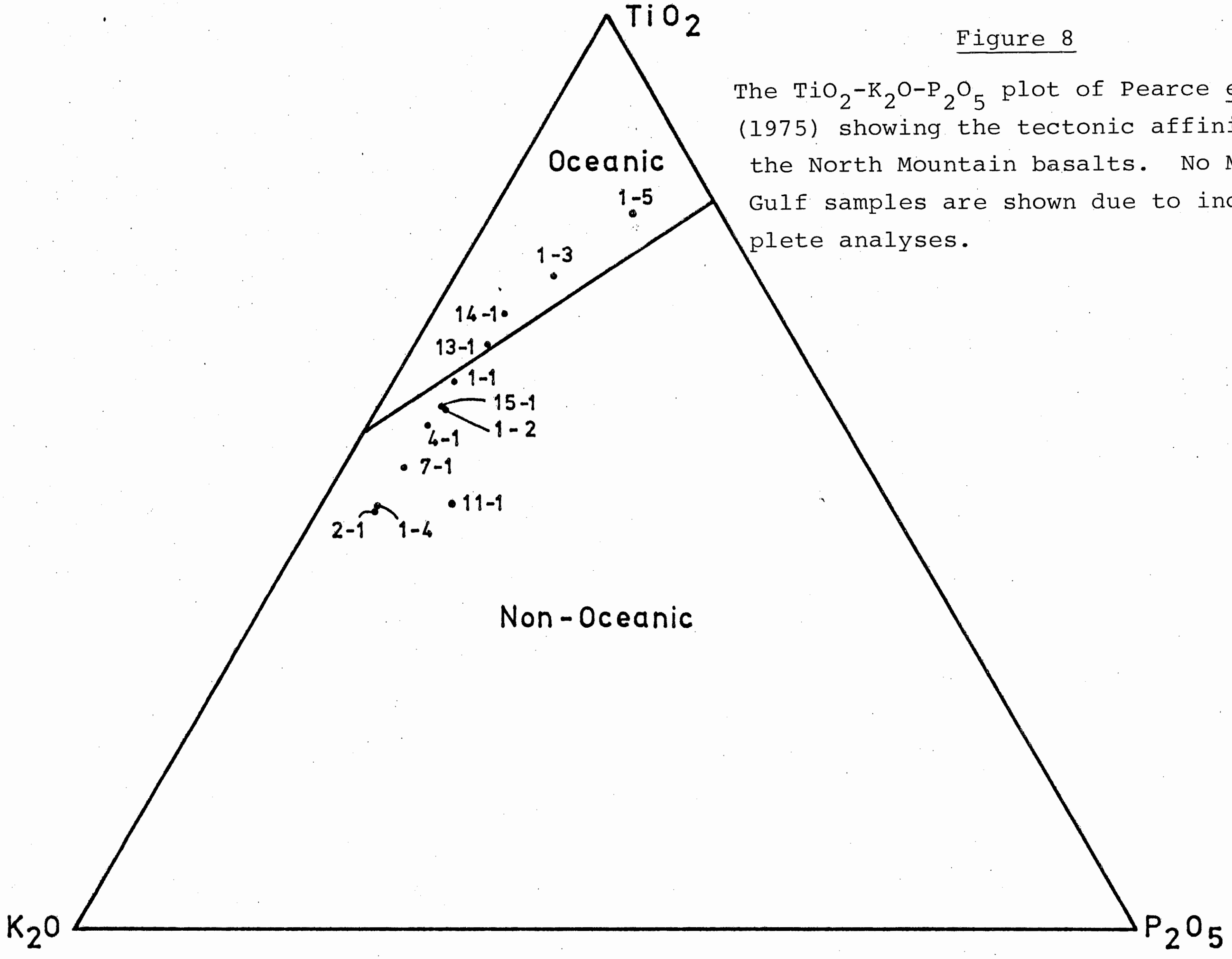


Figure 8

The TiO_2-K_2O-P_2O_5 plot of Pearce et al. (1975) showing the tectonic affinity of the North Mountain basalts. No Mobil-Gulf samples are shown due to incomplete analyses.

The range of variation for K and Rb, previously discussed, is beyond that expected for normal fractional crystallization therefore some secondary process(es) appear to be responsible. The oceanic samples lie more or less along a K_20 control line from the continental samples. The K_20 and other associated elements may have been remobilized by either low grade zeolite facies metamorphism or secondary alteration by hydrothermal fluids. It is not plausible that samples from the same flow can be produced in both oceanic and continental environments.

Gottfried _et_ _al_. (1977), in a similar study of corehole basalts from eastern North America, report that K, Ba, and Rb concentrations vary the most in the altered zones straddling the contact between flow units.

The discriminant diagrams of Pearce (1976) indicate that the North Mountain basalts are low potassium tholeiites (Figures 9 and 10).

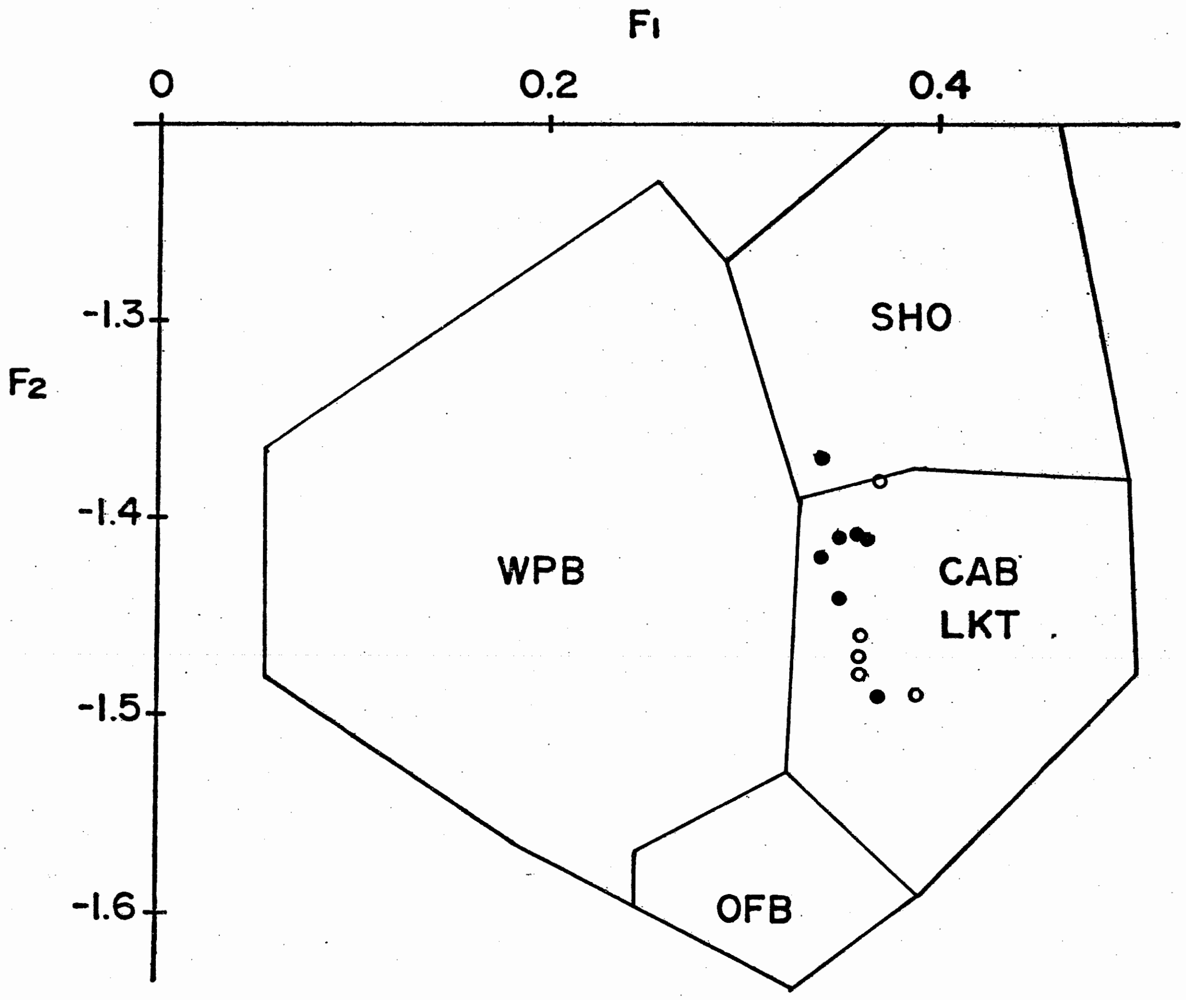


Figure 9

F_1-F_2 plot after Pearce (1976).

WPB = within plate basalt

OFB = ocean floor basalt

CAB = calc alkali basalt

LKT = low potassium tholeiite

SHO = shoshonite

Open circles are from Flow 1

These figures were derived by using discriminant analysis on eight major element oxides, these being: SiO_2, TiO_2, Al_2O_3, FeO (calculated from total Fe), CaO, MgO, Na_2O and K_2O. The various fields of these diagrams were established by plotting basalt samples from known tectonic environments. A maximum of 75 samples from each magma type were used and selected as follows.

1. Only samples with (CaO + MgO) between 12 and 20 percent were used.
2. In general, it had to be possible to assign the analyses to their magma type based on known tectonic setting (i.e. an ocean floor basalt should have 'ocean floor' chemistry.).
3. Analyses had to contain all major element oxides (including H_2O) and sum to between 99 and 101%. Analyses recalculated to 100% were omitted.
4. Only fresh samples were used. Samples described as altered, and samples with $FeO/Fe_2O_3 < 0.5$ were rejected.

The first two discriminant functions (Fig. 9) contain a total of 76.1% of the information available for separating the magma types. The use of F_3 adds a further

12.4% of discriminating power (Pearce, 1976, p.22). The F_1, F_2 and F_3 values were calculated as follows.

$$F_1 = +0.0088\ SiO_2 - 0.0774\ TiO_2 + 0.0102\ Al_2O_3 + 0.0066\ FeO - 0.0017\ MgO - 0.0143\ CaO - 0.0155\ Na_2O - 0.0007\ K_2O$$

$$F_2 = -\ 0.0130\ SiO_2 - 0.0185\ TiO_2 - 0.0129\ Al_2O_3 - 0.0134\ FeO - 0.0300\ MgO - 0.0204\ CaO - 0.0481\ Na_2O + 0.0715\ K_2O$$

$$F_3 = -\ 0.0221\ SiO_2 - 0.0532\ TiO_2 - 0.0361\ Al_2O_3 - 0.0016\ FeO - 0.0130\ MgO - 0.0237\ CaO - 0.0614\ Na_2O - 0.0289\ K_2O$$

Pearce (1976) suggests that only a few analyses are required to express the chemical variation of basalts from any one locality and that all other analyses from the same place serve only to weight the magma type in question in favour of the chemistry of this particular locality.

"On no function could the ocean island and continental basalts be distinguished." (Pearce, 1976) so they have been grouped together in the within-plate basalt field (WPB). This problem was encountered by other discriminating techniques (Pearce and Cann, 1973; Floyd and Winchester, 1975). The F_1 - F_2 diagram could not successfully distinguish between low potassium tholeiites and calc-alkali basalts. The $F_2 - F_3$ diagram (Fig.10) is an attempt to better separate the volcanic arc subdivisions from each other as well as from the ocean floor basalts.

The apparent success rate for classifying the five magma types is about 90% for the diagrams used in this study and it is likely that such a high success rate will not be achieved in classifying rocks of unknown tectonic affinity (Pearce, 1976). This is because Pearce (1976) has used fresh material in establishing his field boundaries and rocks which are not so fresh may have had their major elements remobilized by a number of geologic processes.

The usefulness of this discriminating technique will be greatly dependent on the mobility of the major element oxides. Available evidence indicates that most of the major elements are very susceptible to secondary processes of weathering and metamorphism (Pearce, 1976). Aumento (1965), and Aumento and Friedlander (1966) demonstrated these basalts have been subjected to zeolite facies metamorphism and Vilks (1978) has suggested the grade may be as high as the scolecite-laumontite zone of Walker (1966 a). The major element analyses (Table 4) indicate that certain elements (K_2O, Na_2O, CaO, SiO_2 and TiO_2) have been remobilized. The petrography of these samples shows the feldspars have been zeolitized and the possibility of spilitization in the Mobil-Gulf samples suggest mobility of calcium and sodium. The variation of K_2O (and possibly TiO_2) appears to be due to hydrothermal fluids. The SiO_2 variation is more difficult to explain. Some post-crystallization movement of these elements has occured, however, the extent of remobilization is not known. The points plotted of Figures 9 and 10 may or may not reflect the original rock chemistry so it is felt that great confidence cannot be assigned to deductions based on these figures. Nevertheless, these diagrams do present some useful information. The North Mountain basalts are not OFB or CAB based on these diagrams. Sample MG-10 from the Bay of Fundy plots as a calc-alkaline basalt but it is believed that this is a function of the relatively high Na_2O concentration.

Trace Elements

Figure 11 is a plot of $(Ti \times 10^{-2})$-Zr-$(Y \times 3)$ after Pearce and Cann (1973). The scaling factors on titanium and yttrium bring the points into the centre of the triangle without altering their relative position. This figure shows that all but two North Mountain samples

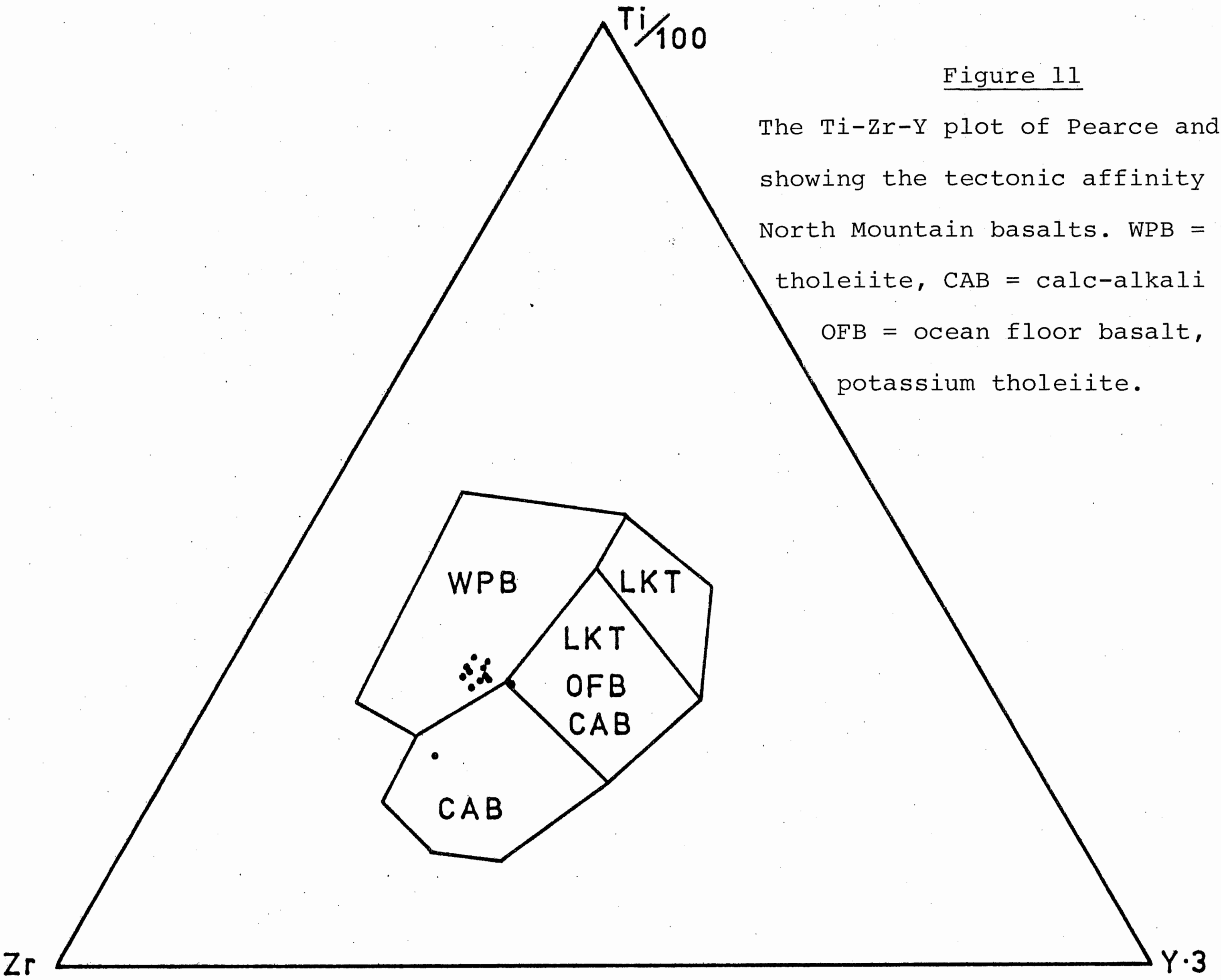


Figure 11

The Ti-Zr-Y plot of Pearce and Cann (1973) showing the tectonic affinity of the North Mountain basalts. WPB = within-plate tholeiite, CAB = calc-alkali basalt, OFB = ocean floor basalt, LKT = low potassium tholeiite.

(1-5 and 11-1) fall in the within-plate basalt field. It was not possible to plot the Mobil-Gulf samples as analyses did not include these elements for all samples. Pearce and Cann (1973) found that it was not possible to chemically distinguish ocean island from continental basalts so they are grouped together in the within-plate basalt field. No attempt was made to define a field for shoshonites (Pearce and Cann, 1973, p. 292).

In choosing samples suitable for the purpose of discriminating between magma types of the various tectonic environments, the following criteria were used.

1. It had to be possible to assign the sample to a known tectonic environment.
2. Samples had to be fresh, but a small number of altered ocean floor samples were used in diagrams not involving Sr.
3. Only analyses comparable to, or better than, the analyses used by Pearce and Cann were chosen from the literature.
4. Basaltic rocks selected from the literature had to pass the screen; $20\% > (CaO + MgO) > 12\%$.

Cann (1970), in his investigation of ocean floor basalts, found that Ti, Zr, Y, and Nb contents remained unchanged throughout processes of weathering and metamorphism. He also found a close correlation worldwide between Zr and Ti and Y and Ti in ocean floor basalts. On this basis he suggested that these elements may be a powerful method of identifying ocean floor basaltic rocks even after profound secondary processes have occurred.

Smith and Smith (1976) studied the distribution of Ti, Zr, Y, Sr, K, P, and Nb in fifty-five samples of Ordovician basalts which have been subjected to prehnite-pumpellyite facies metamorphism. They found that Ti Zr, and Y were 'immobile' through metamorphism; Nb and P were relatively immobile and plots involving Sr or K showed a wide scatter of points.

The results of Cann (1970) and Smith and Smith (1976) serve to demonstrate the immobility of Ti, Zr and Y under various conditions of metamorphism and alteration processes. These studies provide further evidence that the $(Ti \times 10^{-2})$-Zr-(Yx3) plot may be very useful in determination of paleotectonic environment. The value of this plot will depend upon the accuracy of the analyses for these trace elements. Accuracy values for Y and Zr are high (Appendix B, Table B-1). No accuracy values for Ti could be determined but Table 5 indicates that these values are very good.

Pearce and Cann (1973) proposed that Y/Nb ratios could be used on altered volcanics to determine whether they are alkalic or tholeiitic in nature. The North Mountain samples were not so altered as to disguise their petrogenetic affinity. They are clearly tholeiites. The Y/Nb ratios were calculated to see if consistent results could be obtained.

Table 13

Sample	Y/Nb	Classification
1-1	2.7	WPB tholeiite
1-2	3.0	WPB tholeiite
1-3	1.6	OFB alkalic
1-4	1.6	OFB alkalic
1-5	1.9	OFB alkalic
2-1	1.6	OFB alkalic
4-1	2.1	WPB tholeiite
7-1	2.0	WPB tholeiite
11-1	1.9	OFB alkalic
13-1	1.7	OFB alkalic
14-1	1.9	OFB alkalic
15-1	2.6	WPB tholeiite
MG-4	2.3	WPB tholeiite
MG-5	2.0	WPB tholeiite
MG-7	2.0	WPB tholeiite
MG-11	2.1	WPB tholeiite

$\bar{X} = 2.1$

$S = 0.4$

Classifications in Table 13 are based on the criteria given in Table 14 after Pearce and Cann (1973). Based on Tables 13 and 14 it can be concluded that these basalts are not WPB alkalic or OFB tholeiites.

Table 14 Basalt Classification Based on Y/Nb Ratios

Classification	Y/NB
WPB alkalic	1 <
OFB alkalic	> 1 but < 2
WPB tholeiite	> 2 but < 3
OFB tholeiite	> 3

The Y/Nb ratios generally do not give results consistent with the normative compositions. Several North Mountain samples have alkalic affinity based on the Y/Nb ratio and all the Mobil-Gulf samples are tholeiitic. The Ti, Y and Zr values are reliable and the Y/Nb ratios give inconsistent results, so we are led to believe that Nb is the cause of discrepancy. This appears to be analytical error; precision for Nb is high but accuracy is low.

Floyd and Winchester (1975) used the elements Ti, Zr, Y, Nb, and P to produce a set of various binary diagrams which have their greatest usefulness in discriminating between alkaline and tholeiitic basalts. There is a wide overlap of the various fields in all their diagrams and as with other workers (Pearce and Cann, 1973; Pearce 1976), their diagrams could not separate continental and oceanic within-plate tholeiites. Their diagrams were not employed in this study.

Rare-Earth Elements

The rare-earth abundances (Table 8), when chondrite normalized to the values quoted by Frey *et al*. (1968), reveal that the North Mountain basalts have a light rare-earth enriched pattern (Fig.12). This pattern is not characteristic of either ocean floor basalts (REE depleted) or island arc tholeiites ('flat' patterns), but rather shows the within-plate affinity of these basalts (Frey *et al*., 1968; Jakes and Gill, 1970; Schilling, 1971; Jakes and White, 1972). The inset diagram of Figure 12 shows the average abundance of chondrite normalized rare earths for mid-oceanic ridges (solid black circles) and plateau basalts (open circles). The two dotted lines delineate the maximum deviation from the mean for mid-ocean ridge tholeiites (Schilling, 1971, Fig. 5). The mid-ocean ridge tholeiites were averaged from the East Pacific Rise, Mid-Atlantic Ridge, Carlsberg Ridge and the Red Sea Axial Trough. Plateau basalts were averaged from the Columbia Plateau and the Deccan basalts. Jakěs and Gill (1970) have shown that the REE patterns of island arc tholeiites are indistinguishable from those of the oceanic ridge tholeiitic basalts. The North Mountain basalts have an REE pattern similar to the Eastern North America high - Ti, quartz-normative diabases (Fig.13).

The absolute REE abundances from the different samples

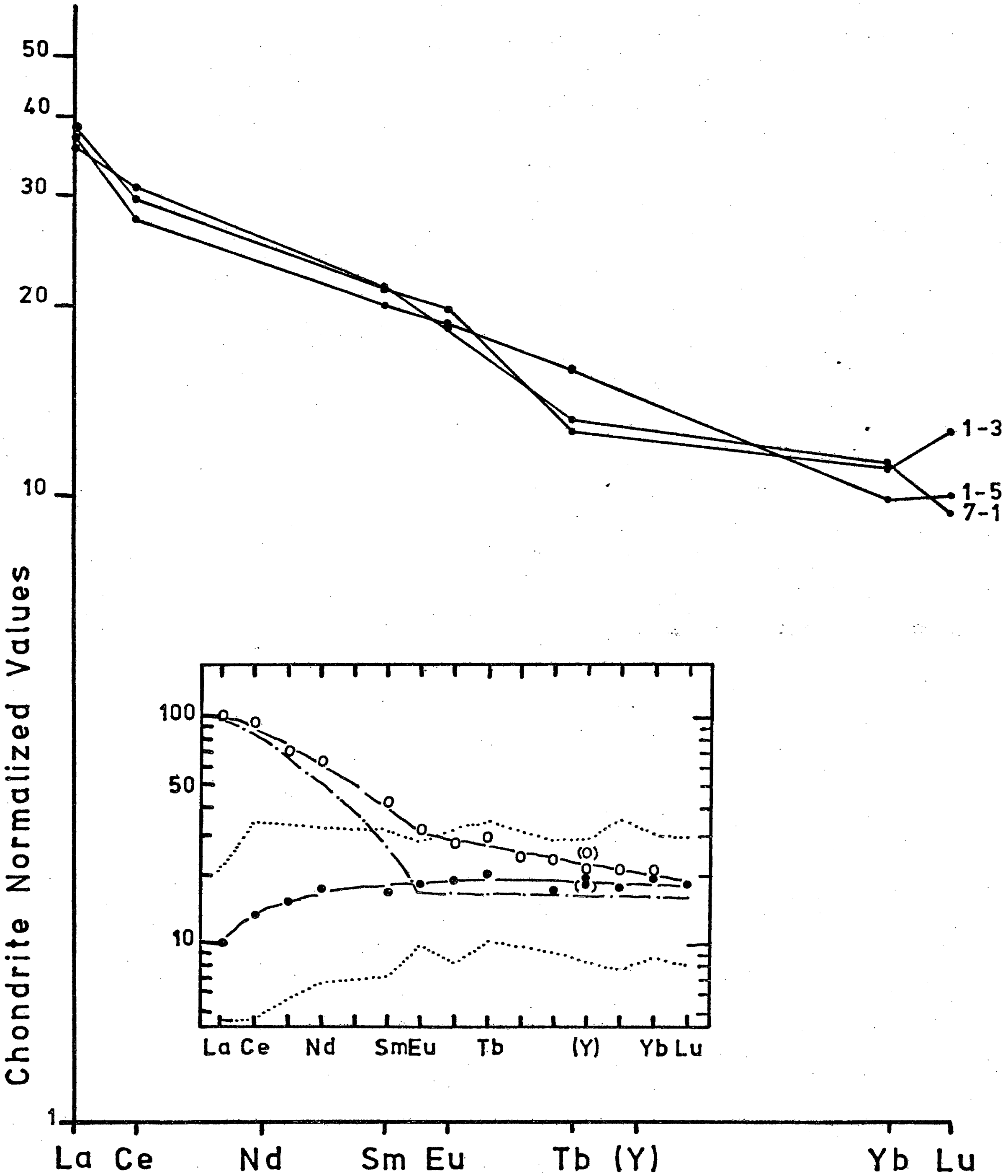


Figure 12

REE abundances chondrite normalized using the values of Frey _et_ _al_. (1968). The basalts have a light REE enriched pattern characteristic of continental basalts.

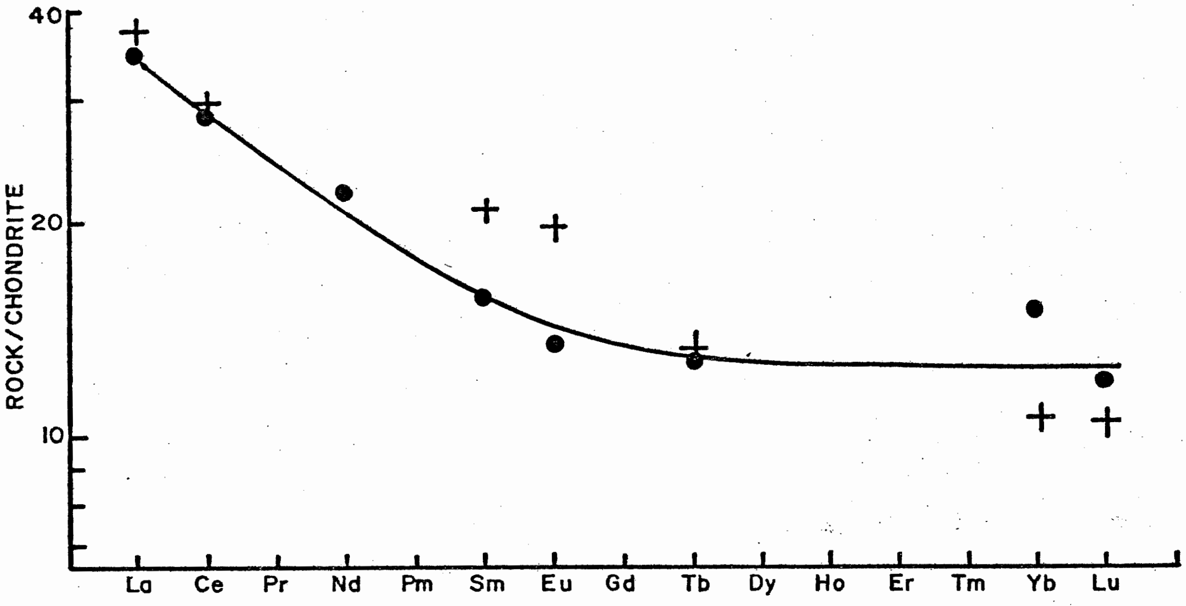


Figure 13

North Mountain REE pattern (+) compared to the ENA high - Ti, quartz-normative diabases (Data from Gottfried et al., 1977). The North Mountain samples are relatively enriched in Sm and Eu and relatively depleted in Yb and Lu. Despite these differences, the patterns are generally similar.

are nearly identical. This may mean one of several things. The REE abundances in the North Mountain were uniformly distributed to begin with and have remained unchanged or they could have been irregularly distributed and alteration has fortuitously brought the concentrations to the same levels. The third possibility is that the abundances were originally the same and were not greatly affected by alteration so that the post-alteration concentrations are now the same. The latter possibility is most probable since sample 1-5 which is the most chemically altered of the North Mountain rocks has the same abundances as 1-3 and 7-1. This is important as it probably demonstrates the immobility of the REE in North Mountain through low grade metamorphism and secondary alteration.

Mineral Analyses

A total of 147 'augitic' clinopyroxene grains were analysed on the electron microprobe. Accuracy and precision data for the analysis are given in Appendix B. Discriminant analysis were applied to the data to calculate the discriminant functions, F_1 and F_2 (Nisbet and Pearce, 1976).

$$F_1 = -0.012 \times SiO_2 - 0.0807 \times TiO_2 + 0.0026 \times Al_2O_3 - 0.0012\ FeO^* - 0.0026 \times MnO + 0.0087 \times MgO - 0.0128 \times CaO - 0.0419 \times Na_2O$$

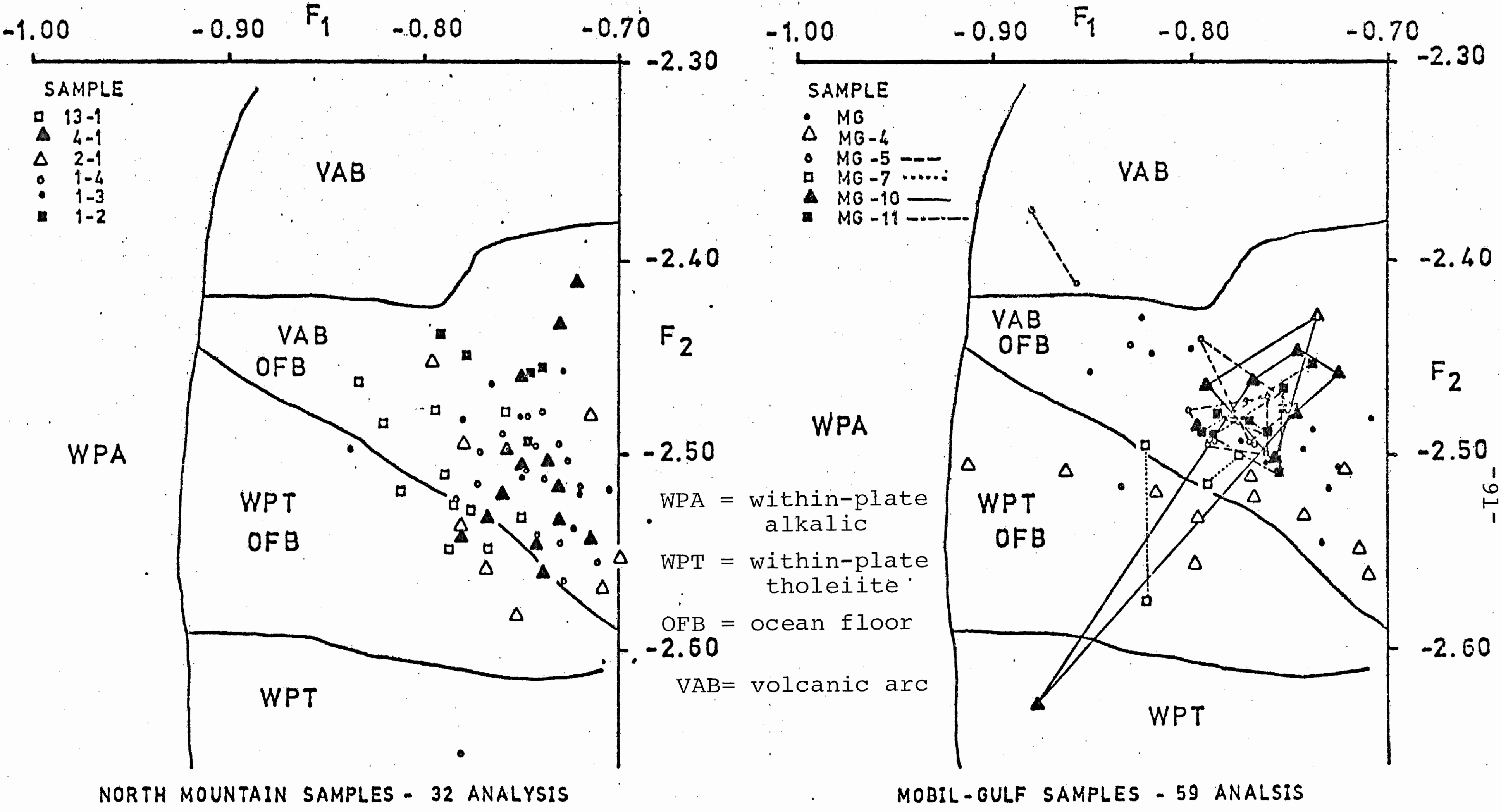
$$F_2 = -0.0469 \times SiO_2 - 0.0818 \times TiO_2 - 0.0212 \times Al_2O_3 - 0.0041 \times FeO^* - 0.1435 \times MnO - 0.0029 \times MgO + 0.0085 \times CaO + 0.0160 \times Na_2O$$

The results of the analyses are plotted of Figures 14 and 15. Figure 14 shows each clinopyroxene grain analysed and includes both phenocrysts and groundmass grains. This figure is not only confusing but somewhat inconclusive. Figure 15 is an attempt to simplify things by plotting only the means of all analyses and error bars to the two standard deviations.

Figure 14 shows that both the North Mountain and Mobil-Gulf samples have a wide scatter of points but the majority of the analyses plot in the field of overlap of volcanic arc basalts (VAB) and ocean floor basalts (OFB). Figure 15 shows the mean values plot in the field of overlap of VAB and OFB as well, with a wide spread. These figures suggest the basalts are either volcanic arc or ocean floor. This is at variance with other discriminating techniques previously presented, which indicate the basalts are primarily continental (Figures 7,8, 11 and 12). Volcanic arc basalts are continental but the REE patterns are not typical of volcanic arc basalts (Jakěs and Gill, 1970).

Nisbet and Pearce (1977) found that this method of discriminating tectonic environments has an overall average success rate of only 69.5%. Within plate alkalic basalts (WPA) and ocean floor basalts (OFB) have the greatest success, being 89.0% and 87.8%, respectively. Volcanic arc basalts (VAB) and within plate tholeiites (WPT) have success rates of 58.9% and 42.3%, respectively. The fact that the within plate tholeiites have such a low success rate may be due to the fact that Nisbet and Pearce used only 26 samples to define their field boundaries. Twenty-six samples on a world-wide basis may not be statistically significant.

Nisbet and Pearce (1977) concluded that this technique may put some constraints on tectonic environment of eruption and thus supplement the immobile trace element techniques. They showed (p.159) that the trace element diagrams could achieve better separation than their pyroxene diagrams. Figures 14 and 15 do suggest that the North Mountain and Mobil-Gulf basalts are not within plate alkali basalts.

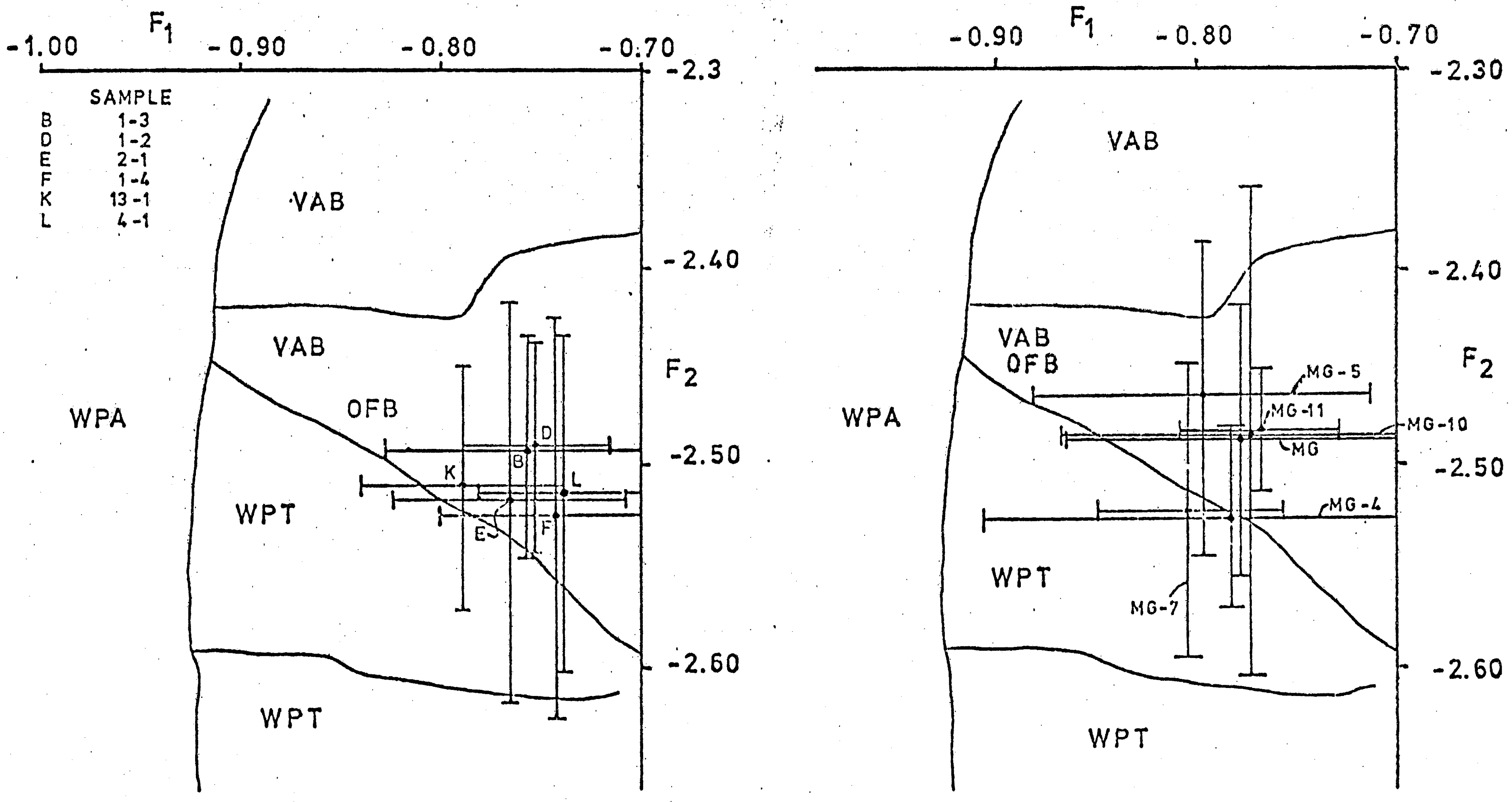


NORTH MOUNTAIN SAMPLES - 32 ANALYSIS

MOBIL-GULF SAMPLES - 59 ANALSIS

Figure 14

F_1-F_2 diagram after Nisbet and Pearce (1977) showing the tectonic affinity of the North Mountain and Mobil-Gulf basalts.



NORTH MOUNTAIN SAMPLES- 32 ANALYSES

MOBIL-GULF SAMPLES - 59 ANALYSES

<u>Figure 15</u>

F_1-F_2 diagram after Nisbet and Pearce (1977) showing the mean values and error bais to the second standard deviation Fields are the same as Fig. 14 .

Tectonic Implications

The Eastern North American dolerite dikes and associated volcanic flows are spatially, temporally, and probably genetically associated with Triassic rift valleys of eastern North America (Weigand and Ragland, 1970). Bertrand and Coffrant (1977) have suggested these magmatic events are related to early tension lines which initiated the opening of the North Atlantic. Pitman and Talwani (1972) suggest the initiation of rifting between Africa and North America may have occurred 200 m.y. ago but that the active phase of drift did not begin until 180 m.y. ago.

Potassium-argon age dates of the North Mountain Basalt coincide with the initiation of rifting suggested by Pitman and Talwani (1972). This seems to indicate that the North Mountain Basalt was erupted in a tensional environment prior to initiation of continental drifting and genesis of new crustal material at spreading centres. The presence of continental sediments above and below the North Mountain Basalt is good supportive evidence that these basalts were in fact erupted in a continental environment. If these basalts are continental, the discriminant diagrams should verify this.

The REE plot (Figure 12) suggests the North Mountain basalts were erupted in a within-plate environment. Other plots suggest these basalts are predominantly continental with some oceanic affinity (Figures 7 and 8). Pearce _et_ _al_. (1977) found that Triassic and Jurassic continental basalts worldwide tend to have oceanic affinities. They suggested that during continental rifting, basalts of a somewhat oceanic character are produced. The Tertiary basalts of Baffin Bay are continental but exhibit oceanic affinity on the Ti-Zr-Y plot of Pearce and Cann (1973), (Clarke, 1970). These basalts are related to continental rifting and Floyd and Winchester (1975) suggest that the oceanic floor field of the Ti-Zr-Y plot represents not only ocean floor basalts but all tholeiitic basalts formed in a rifting environment.

Schilling (1971), in an extensive study of sea-floor basalts, suggested there is a volcanic sequence for continental drift and sea floor spreading repeated systematically regardless of time and space. This is: 1) continental eruptions of tholeiitic plateau basalts enriched in larger electro-positive trace element ions at the onset of drifting of continental blocks of lithosphere, followed later by (2) eruption along oceanic rifts of tholeiites depleted in these larger ions. The REE patterns of phase (1) and (2) above are distinctly different (Schilling, 1971). The REE have been shown to be 'immobile' through various geologic processes. As a result of this, it is felt that great confidence can be used when identifying various tectonic environments with REE abundances.

The immobile trace elements Ti-Zr-Y indicate the North Mountain basalts were erupted in a within plate environment. In conjunction with the REE pattern, these trace elements strongly suggest the North Mountain Basalt was erupted in a continental, within-plate environment.

Summary

The results of the various discriminant diagrams presented earlier are summarized in Table 15.

Table 15 Tectonic Environments Indicated by the Various Discriminating Techniques.

Discriminator	Figure	Environment Indicated
$FeO^*-MgO-Al_2O_3$	7	Continental, some oceanic affinity
$TiO_2-K_2O-P_2O_5$	8	Continental, some oceanic affinity
Major Elements F_1-F_2	9	Calc-alkalic, low potassium tholeiites, shoshonites
Major Elements F_2-F_3	10	Low potassium tholeiites
Ti-Zr-Y	11	Within-plate basalt
REE	12	Within-plate
Clinopyroxene F_1-F_2	14,15	Ocean floor, volcanic arc

Figures 7 and 8 are straightforward, indicating a continental environment with some tendency toward oceanic affinity. The elements used in these plots have been shown to be relatively unaffected by low grade metamorphic alteration processes to which the North Mountain has been subjected.

Figures 9 and 10 cannot be used with great confidence. It has been demonstrated that several elements used in computing the F_1 and F_2 values have been remobilized. These figures indicate the North Mountain volcanics are low potassium tholeiites. Low potassium tholeiites are commonly associated with early magmatic activity in volcanic arc environments. The REE pattern does not support a volcanic arc environment.

Figure 11 can be used with high confidence as Ti, Zr, and y remain immobile throughout a host of geologic processes. The same applies for Figure 12 (Frey et al., 1968; Schilling, 1971; Pearce and Cann, 1973; Smith and Smith, 1976). These figures indicate a continental within-plate environment.

Figures 14 and 15 indicate ocean floor and/or volcanic arc environments. Once again the REE pattern precludes this classification.

Considering all the discriminator diagrams together, the North Mountain basalts are continental, within plate tholeiites with a small tendency toward oceanic affinity. Pearce et al.(1977) suggest that basalts of this age erupted in a tensional environment should have a tendency toward 'oceanic' chemistry.

CHAPTER 7

CONCLUSIONS

Based on the discriminant diagrams, it is seen that several interpretations are suggested for the environment of eruption of the North Mountain basalts. Some of the environments indicated (Table 15) may be safely disregarded by the process of elimination. Strong confidence is placed upon plots involving Ti, Zr, Y and the REE.

Chemical evidence alone suggests the North Mountain basalts (and probably the Mobil-Gulf basalts) were:

1) erupted in a within-plate regime
2) this regime was continental with some indication of an oceanic character.

The within-plate, continental interpretation agrees well with the geologic field evidence, i.e. continental sediments immediately above and below the basalts with no unconformity contacts.

Although these discriminant techniques appear to be useful in determining paleotectonic environment, it is felt that no single technique can be applied alone. A combination of these techniques in conjunction with geological field relations must be used to get a reasonable idea of the paleotectonic environment. This applies to any study of this type.

The North Mountain basalts are interpreted to be pre-continental break up, rift type volcanics formed prior to the separation of North America and Africa in Jurassic time.

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APPENDIX A

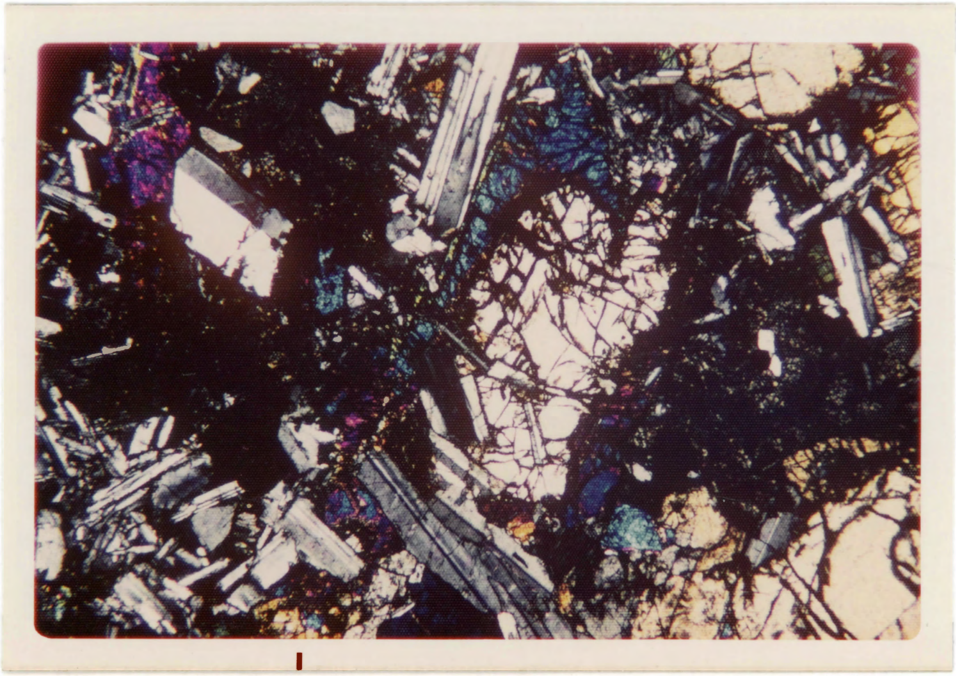


Plate 1

Large opx grain mantled by augite. Note the freshness of both the plagioclase and augite (Sample 1-2)

Plate 2

Although slightly out of focus, this slide shows the ophitic texture common in the coarser grained basalts. The dark patches are not glass, but magnetite (Sample 1-1)

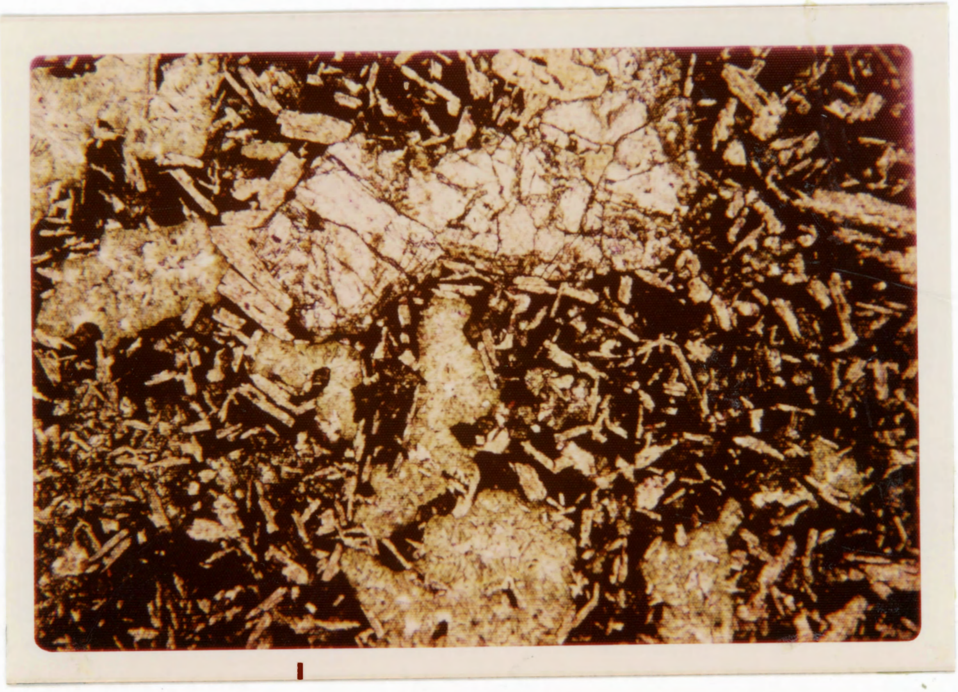


Plate 3

Note the chlorite filling amygdules, extensive sericitization of the plagioclase and abundant intersertal magnetite. The large augite crystal is unaltered except along fractures. PPL. (Sample MG-2)

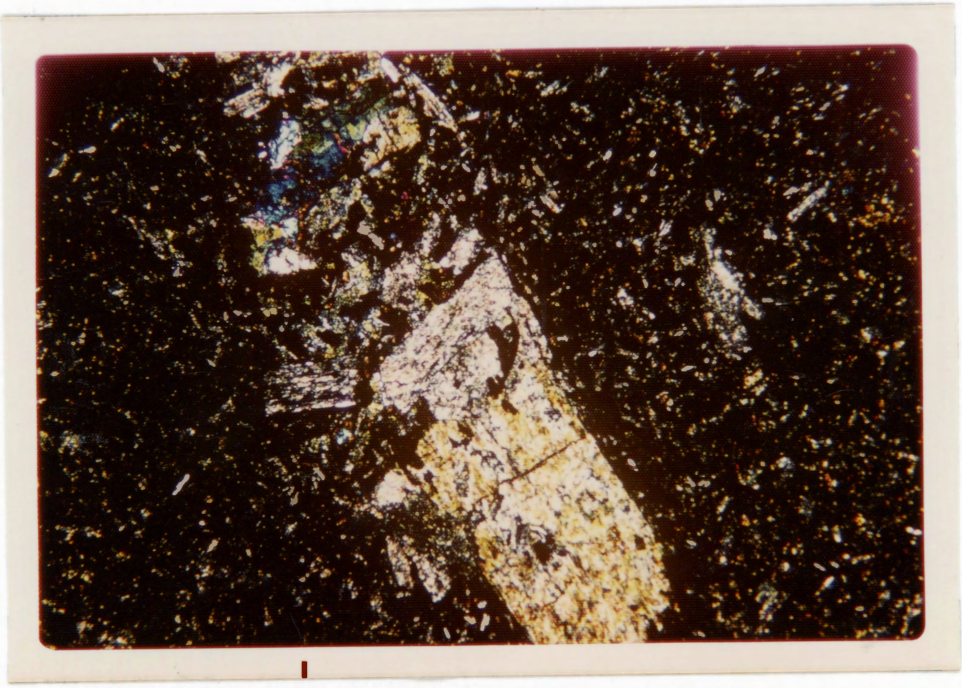


Plate 4

Pseudomorph of chlorite after augite. Note the aphanitic groundmass containing abundant magnetite and sericite alteration of plagioclase (Sample MG-1)

Slide GAV-77-3A **Location:** D.D.H. at Morden

Sample 1-1

Description

Minerals	Estimated Modal %	Description
Augite, includes pigeonite	50	As phenocrysts, glomeroporphyritic clusters and groundmass grains. Pigeonite occurs as groundmass grains and forms the core of larger grains rimmed by augite
Plagioclase	40	Occurring as phenocrysts and anhedral groundmass grains. Polysynthetic twinning is common and some phenocrysts show oscillatory zoning.
Magnetite	3	As anhedral intergranular grains in the groundmass and euhedral crystals in devitrified glass patches.
Unidentified brown patches, possible pseudomorphs after glass	6	Very fine grained, fibrous aggregates
Devitrified glass	1	Dark patches showing intersertal texture.

Textures: Granular, Porphyritic with phenocrysts of augite and plagioclase, medium to fine grained

Alteration: Feldspars and clinopyroxenes are relatively fresh. Some clay minerals along fractures in the feldspar crystals. The glass originally present has all been devitrified. One of the least altered samples.

Slide GAV-77-3D **Location:** D.D.H. at Morden

Sample 1-2

Description

Minerals	Estimated Modal %	Description
Augite, includes pigeonite	40	As anhedral grains, frequently twinned. Pigeonite occurs as groundmass grains and forms the core of larger grains rimmed by augite.
Plagioclase	50	As euhedral laths. Polysynthetic twinning is common. Some crystals show oscillatory zoning, others are strongly, normally zoned
Magnetite	5	As primary, irregular grains and also as a secondary mineral
Brown alteration patches	5	As described for sample 1-3
Enstatite (?)	1	Forming the core of larger grains rimmed by augite.
Clay minerals Zeolites Chlorite	2	As secondary alteration minerals

Textures: Holocrystalline, Doleritic, Opx mantled by Augite, Medium grained.

Alteration: Alteration is minor. Chlorite filling fractures in augite. Clay minerals and minor zeolitization on some plagioclase crystals.

Slide GAV-77-3B **Location:** D.D.H. at Morden

Sample 1-3

Description

Minerals	Estimated Modal %	Description
Augite, includes pigeonite	45	As anhedral grains often showing sub-ophitic to ophitic texture. Pigeonite occurs as described in sample 1-1
Plagioclase	40	As phenocrysts and euhedral to subhedral laths in the groundmass. Some crystals show oscillatory zoning. An_{59}.
Magnetite	3	As euhedral to subhedral grains closely associated with devitrified glass patches. Also as acicular needles in red-brown patches.
Devitrified glass	10	Black, irregular patches containing acicular or euhedral magnetite.
Brown alteration	2	As interstitial patches containing fine grained silicates and long skeletal oxides. Some of these brown patches are pseudomorphs after olivine.

Textures: Ophitic to sub-ophitic, Holocrystalline, Granular Aphanitic.

Alteration: Feldspars and clinopyroxenes are unaltered with the exception of minor oxidation minerals (hematite?) on some grains near the brown patches.

Slide GAV-77-3F **Location:** D.D.H. at Morden

Sample 1-4

Description

Minerals	**Estimated Modal %**	**Description**
Augite, includes pigeonite	35	Occurs mostly as groundmass grains but some phenocrysts. All anhedral.
Plagioclase	45	As euhedral to subhedral phenocrysts and groundmass laths.
Magnetite	4	Intersertal grains and secondary alteration rims.
Altered glass	5	Nearly black - may be due to very fine grained magnetite.
Brown alteration patches	10	Brown to green pleochroism. Occurs as alteration patches on both feldspars and augite, also filling vesicles and holes.
Olivine	1-2	Replaced by brown mineral which may be iddingsite.

Textures: Aphanitic with microphenocrysts of plagioclase and augite, Intersertal, sub ophitic, quenched.

Alteration: Augite altered to chlorite and secondary magnetite. Feldspars appear relatively fresh with minor sericite along cleavage planes.

Slide GAV-77-3C **Location:** D.D.H. at Morden

Sample 1-5

Description

Minerals	Estimated Modal %	Description
Augite	40	As phenocrysts and anhedral groundmass grains.
Plagioclase	30	As phenocrysts, euhedral groundmass laths and microlites.
Magnetite	2	As small, euhedral to subhedral crystals in devitrified glass patches and as subhedral grains in the groundmass
Altered glass	25	As red brown intersertal patches containing magnetite and sometimes feldspar microlites
Opal (?), chalcedony, quartz and zeolites	3	Filling irregularly shaped cavities. the amygdules are concentrically zoned with quartz forming the rims and the centres filled with intergrown aggregates of opal, chalcedony and zeolites.

Textures: Intersertal (magnetite and glass), Porphyritic with phenocrysts of augite and plagioclase. Glomeroporphyritic aggregates of augite and plagioclase, Amygdaloidal, Aphanitic (quenched rock).

Alteration: Clay minerals along cleavage of feldspars and as patches.

Slide GAV-77-3E **Location:** D.D.H. at Morden

Sample 2-1

Description

Minerals	Estimated Modal %	Description
Augite, includes Pigeonite	45	Occurs as phenocrysts and groundmass grains,Pigeonite occurs as groundmass grains.
Plagioclase	Original 40 now 16	As euhedral to subhedral phenocrysts and groundmass laths. Extensively replaced by zeolites and clay minerals.
Magnetite	5 - 10	As euhedral to anhedral groundmass grains
Zeolites (mostly stilbite + natrolite)	24	As alteration of the feldspars.
Green patches (chlorite?)	4	Very fine grained mineraloid (?) filling cavities.
Chalcedony	1	As vesicle margins
Chlorophaeite (?)	1	As pseudomorphs after olivine.

Textures: Porphyritic, glomeroporphyritic with phenocrysts of augite and plagioclase. Amygdaloidal, Aphanitic groundmass. The slide is heterogeneously altered.

Alteration: Feldspars are extensively zeolotized with minor chlorite and clay minerals. One side of the slide is blacker under X-nicols and contains more magnetite, much of which is secondary. One of the most altered slides. Olivine replaced by chlorophaeite (?).

Slide GAV-77-3L **Location:** D.D.H. at Morden

Sample 4-1

Description

Minerals	Estimated Modal %	Description
Augite, includes pigeonite	40	As phenocrysts and anhedral groundmass grains.
Plagioclase	Original 40 Now 36	Primarily as groundmass laths but also as phenocrysts.
Magnetite	5	Euhedral to anhedral groundmass grains.
Zeolites -analcite -stilbite	11	7% filling vesicles and 4% as alteration of plagioclase.
Unidentified, bright green mineral	3	Filling irregularly shaped vesicles and invariably associated with a brown oxide.
Sericite	1	As alteration along cleavage of plagioclase crystals.
Chlorite	1	Alteration of some augite and often in vesicles.
Brown mineral (clays)	5 -7	As alteration patches and reaction rims around some chlorite vesicles.

Textures: Glomeroporphyritic clusters of augite and plagioclase, amygdaloidal, quenched (very fine grained). The amygdules are very irregularly shaped and sometimes filled with a bright green mineral (mineraloid?).

Alteration: Groundmass augite is cloudy with brownish clay minerals. Feldspars are sericitized and zeolitized. Secondary magnetite may rim augite (not common). Chlorite is sporadic but selectively alters the augite.

Slide GAV-77-3G **Location:** D.D.H. at Morden

Sample 7-1

Description

Minerals	Estimated Modal %	Description
Augite	60	As phenocrysts and anhedral groundmass grains.
Plagioclase	Original 24 Now 14	As phenocrysts and groundmass laths. Extensively zeolotized.
Magnetite	6	Groundmass grains
Amygdules chlorite Quartz	5	Filling rounded to irregularly shaped cavities.
Zeolites - stilbite - analcite	15	As amygdules and alteration of feldspars
Olivine Iddingsite	1	Subhedral groundmass crystals replaced by iddingsite.

Textures: Porphyritic with phenocrysts of plagioclase and augite Amygdaloidal, Aphanitic groundmass. Relict plagioclase and olivine.

Alteration: Plagioclase has been extensively replaced by zeolites. A ubiquituous brown mineral on groundmass augite may be hematite staining. Larger augite grains are relatively unaltered except along fractures (chlorite). Where plagioclase is ophitic in augite, the plagioclase is selectively zeolotized.

Slide GAV-77-3N **Location:** D.D.H. at Morden

Sample 11-1

Description

Minerals	**Estimated Modal %**	**Description**
Augite	40	As glomeroporphyritic clusters and anhedral groundmass grains.
Plagioclase	Original 45 Now 36	Glomeroporphyritic clusters with augite and as groundmass laths.
Magnetite	3	As euhedral to subhedral ground mass grains almost invariably associated with a brown oxide or chlorite.
Zeolites	10	9% as alteration of plagioclase and 1% filling vesicles.
Chlorite	2	In vesicles and also as alteration of augite.
Sericite	3	As alteration of plagioclase.
Altered glass	5	Blackish, irregularly shaped patches often containing magnetite.
Quartz	1	Rimming vesicles .
Olivine	1	Euhedral to anhedral relict crystals.

Textures: Glomeroporphyritic clusters of augite and plagioclase, relict olivine and augite, amygdaloidal. The fine grain size suggests rapid cooling .

Alteration: Some augite phenocrysts have been completely replaced by chlorite. The feldspars have been sericitized and zeolitized. The olivine has been altered to chlorite and iddingsite.

Slide GAV-77-3K **Location:** D.D.H. at Morden

Sample 13-1

Description

Minerals	Estimated Modal %	Description
Augite	35	As glomeroporphyritic clusters and anhedral groundmass grains.
Plagioclase	Original 50 Now 40	Euhedral to subhedral groundmass laths.
Magnetite	5	As small grains occuring in intersertal patches and as larger, anhedral, groundmass grains. Some is secondary.
Zeolites -stilbite -analcite -natrolite (?) -thompsonite (?)	17	10% as alteration of plagioclase and 7% filling vesicles.
Chlorite	2 - 3	As alteration of augite but most frequently lining vesicles walls.

Textures: Amygdaloidal, aphanitic, porphyritic with phenocrysts of augite.

Alteration: Feldspars have been altered to zeolites and clay minerals. Minor chlorite alteration of some augite. A brown oxide (hematite?) pervasive in cracks and fractures is closely associated with magnetite.

Slide GAV-77-3J **Location:** D.D.H. at Morden

Sample 14-1

Description

Minerals	**Estimated Modal %**	**Description**
Augite	40	As glomeroporphyritic clusters and anhedral groundmass grains. Pigeonite occurs as groundmass crystals forming the core of larger grains rimmed by augite.
Plagioclase	Original 40 Now 36	As euhedral to subhedral groundmass grians and rarely as microphenocrysts.
Magnetite	5	As anhedral groundmass grains commonly in red-brown alteration mineral filling some vesicles.
Zeolites - analcite - stilbite -natrolite (?)	12	8% filling vesicles and 4% as alteration of plagioclase.
Chlorite	2	As alteration of zeolite and filling some small vesicles.
Quartz	2	As rims around amygdules.
Altered glass	1	Intersertal patches
Hematite (?)	2 - 3	Filling fractures and along borders of some augite grains.

Textures: Very amygdaloidal, porphyritic with phenocrysts of augite and some plagioclase. Quartz rimming amygdules which are irregularly shaped.

Alteration: Feldspars are moderately altered to zeolites and clay minerals. Alteration of augite is minor with secondary hematite. Some zeolite filling vesicles has been chloritized.

Slide GAV-77-31 **Location:** D.D.H. at Morden

Sample 15-1

Description

Minerals	Estimated Modal %	Description
Augite, includes pigeonite	45	Mostly as anhedral groundmass grains but also as phenocrysts up to 3 mm. diameter. Pigeonite occurring as in 1-1.
Plagioclase	original 35 now 14	As euhedral phenocrysts and euhedral to subhedral groundmass laths.
Magnetite	7	Small euhedral to subhedral grains generally restricted to altered glass patches.
Devitrified glass	3	Intersertal, dark patches.
Zeolites -stilbite -analcite -natrolite (?)	24	As alteration of plagioclase and filling vesicles
Quartz	2	Rimming amygdules
Clay minerals (?)	3	As alteration of augite along fractures and grain borders.

Textures: Porphyritic with phenocrysts of augite and plagioclase. Very amygdaloidal, aphanitic groundmass, Intersertal glass, relict plagioclase sub-ophitic.

Alteration: Brownish alteration mineral on augite (clay minerals (?) but augite is not nearly as altered as plagioclase. Plagioclase has been extensively zeolitized. A red mineral occurring in patches may be hematite.

Slide MG-3 **Location:** Mobil-Gulf Chinampas
N-37

Description

Minerals		Estimated Modal %	Description
Augite	Original	30	As phenocrysts and anhedral groundmass laths.
	Now	25	
Plagioclase	Original	45	As phenocrysts and groundmass laths.
	Now	6	
Magnetite		10-12	Euhedral to anhedral grains found in altered glass patches.
Chlorite	up to	10	Filling Vesicles
Sericite clay minerals zeolite (?)		39	As alterations of feldspars
Red-brown hematite		5	As alteration of groundmass augite.
Altered glass		5	Dark irregular patches containing magnetite

Textures: Porphyritic with phenocrysts of augite and plagioclase, Pseudomorphs of sericite and clays after feldspar, vesicular and amygdaloidal with infillings of chlorite. Fine grained (quenched).

Alteration: Feldspars are extensively altered to sericite and clay minerals. Augite in the groundmass is extensively stained by hematite.

Slide MG-2 **Location:** Mobil-Gulf Chinampas
N-37

Description

Minerals		Estimated Modal %	Description
Augite	Original Now	25 20	As phenocrysts and anhedral grains.
Plagioclase	Original Now	40 14	As phenocrysts and anhedral groundmass laths.
Magnetite		15	Euhedral to subhedral crystals primarily in altered glass patches.
Chlorite		10	Filling vesicles
Sericite Clay minerals		36	As alteration of plagioclase
Altered glass		9	Dark, intersertal patches containing magnetite.
Olivine		1	As relict grains.
Biotite		1	Replacing olivine.

Textures: Porphyritic with phenocrysts of augite and plagioclase, amygdaloidal, relict olivine and plagioclase. Pseudomorphs of biotite after olivine and sericite plus clays after plagioclase. Very fine grained, quench texture.

Alteration:

Feldspars have been extensively altered to sericite and clay minerals. Augite is altered in some places on grain borders to hematite whereas other grains are completely replaced by chlorite. Extensive hematite staining.

Slide MG-1

Location: Mobil-Gulf Chinampas
N-37

Description

Minerals	Estimated Modal %		Description
Augite	Original	40	As phenocrysts and anhedral groundmass grains
	Now	20	
Plagioclase	Original	45	Glomeroporphyritic clusters with augite and as groundmass laths.
	Now	9	
Magnetite		6 - 8	As minute euhedral grains in brown altered glass patches and as anhedral groundmass grains.
Sericite Calcium carbonate Clays		36	As alteration of feldspars. Calcium carbonate occasionally filling vesicles.
Chlorite		2 - 3	As alteration of augite
Zeolites		2	Filling vesicles
Brown hematite stain		20	
Olivine		1	

Textures: Glomeroporphyritic clusters of augite and plagioclase. Porphyritic with phenocrysts of augite, Relict olivine and augite, amygdaloidal.

Alteration: The feldspars are extensively sericitized and kaolinized. When augite and plagioclase are in glomeroporphyritic clusters, the plagioclase is selectively altered. Olivine and occasionally augite are replaced by chlorite. Extensive hematite (?) staining pervasive throughout groundmass.

APPENDIX B

APPENDIX B

Sample Preparation

Several hundred grams of basalt from each sample location were reduced to powder. Prior to crushing, the samples were washed and rinsed to remove surficial contaminants. The bulk samples were fragmented in a hydraulic press and crushing was done in a ceramic jaw crusher. If an adequate volume of rock chips was present after crushing, powdering was done in a tungsten carbide swing mill. If a relatively small volume of rock chips remained after crushing, the sample was powdered in a ceramic 'shaker' and subsequently ground by hand with an agate mortar and pestle. The resulting powders were stored in polyethylene bottles and used for all subsequent analysis.

Analytical Methods

The following methods were used to obtain the chemical data presented in Chapters 4 and 5.

1. Atomic Absorption Spectrometry for major and minor elements.
2. Titrimetric Determination of FeO.
3. Colorimetric Determination of P_2O_5.
4. Determination of H_2O .
5. X-ray Fluorescence for trace elements.
6. Instrumental Neutron Activation for rare earths and SiO_2.

7. Electron microprobe for clinopyroxene analysis.

1. Atomic Absorption

Sample decomposition was modified after Warren and Carter (1975). Approximately 0.5 gm. of powder accurately weighed to ± 0.0001 gm. were placed in a teflon cup with 0.5 ml. of water. HNO_3 (2.5 ml.) and a 1:4 mixture of perchloric acid and HF (20 ml.) were added and the samples were put in a steam bath at 100°C overnight. The mixture was then evaporated for about 5 hours and placed in a sand bath to evaporate the perchloric acid. The mixture was cooled to room temperature and the following reagents were added; 5 ml. of water, 5 ml. of concentrated HCl, 15 ml. of 5% boric acid and enough H_2O to fill the cups halfway. The samples were then digested for one hour at 100°C, cooled and transferred to a 250 ml. volumetric flask where they were brought to the mark with distilled water. These solutions were stored in polyethylene bottles and used for Atomic absorption spectrometry on a Perkin-Elmer 503 spectrometer using standard techniques. Element oxides not determined with this method include SiO_2, FeO, P_2O_5, and H_2O. In determining major element oxide concentrations, each solution was run three times to correct for background 'noise'.

2. FeO by Titration

Fe_2O_3 values reported in Table 4 were determined in the following manner. Total iron was determined as Fe_2O_3* by atomic absorption methods discussed above. FeO was determined as follows.

Approximately 0.2 gm. of rock powder was accurately weighed and transferred to a plastic flask. Blanks were run simultaneously. The powder was slurried with 5 ml. of 0.1N ammonium vanadate solution and 10 m. of HF were added. After swirling (overnight) to decompose the sample, 10 ml. of a mixture of H_2SO_4 and H_3PO_4 were added (H_3PO_4: H_2SO_4: H_2O = 1:2:2) and the contents were transferred to a beaker containing 100 ml. of 5% boric acid solution. The flask was rinsed with 100 ml. of the boric acid solution and the washings were also added to the beaker. An automatic pipet was used to add 10 ml. of 0.05 N ferrous ammonium sulphate solution to the beaker and 16 drops of 0.2% barium diphenylamine sulfonate were added.

The mixture was then titrated to a purple end-point with 0.05 N $K_2CR_2O_7$ solution.

$$\% \text{ FeO} = \frac{(\text{ml. for sample-ml. for blank}) \times 0.003593 \times 100}{\text{Wt. in gm.}}$$

Fe_2O_3 was then determined by subtraction

$$Fe_2O_3 = Fe_2O_3{}^* - 1.1113\ FeO$$

3. Colorimetric determination of P_2O_5

Immediately before carrying out the determination, a combined reagent solution was prepared by mixing a) 125 ml. of 3N H_2SO_4, b) 38 ml. of ammonium molybdate, c) 60 ml. of ascorbic acid and d) 27 ml. of H_2O. Five (5) ml. of the sample solution were pipetted into a 50 ml. volumetric flask. A blank was run simultaneously. The combined reagent solution (20 ml.) was added to each flask. The flasks were swirled, diluted to 50 ml. and allowed to stand overnight. The optical density was then measured at 827 mu on a Bausch and Lomb spectrophotometer (Spectronic 70 model), after running a standard solution to calibrate the machine.

4. Determination of H_2O

Total water was determined by mixing sample powder with a fluxing agent and completely melting the sample in Penfield tube. The tube was was weighed both wet and dry and the difference in weight is total H_2O.

H_2O^- was determined by accurately weighing a sample portion and then 'drying' it in a dessicator for several hours. The difference in weight gives the H_2O^- as a percent.

H_2O+ was simply calculated by difference of total water and H_2O^-.

5. X-ray Fluorescence

All the trace elements with the exception of the rare-earth elements were determined on a Philips 1450 XRF spectrometer with an Ag-anode X-ray tube. Peak intensities were corrected for background and line-overlap and then divided by the Compton peak intensity to correct for sample matrix. The resulting intensities were reduced to ppm by comparison to the working curves at Memorial University where the analyses were performed. The precision values for various standards are shown in Table B-1.

TABLE B-1 TRACE ELEMENT DETERMINATIONS BY XRF FOR U.S.G.S. STANDARD ROCKS,
MEMORIAL UNIVERSITY, MARCH 10-20, 1978.

	V	Cr	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Ba	Pb
W-1	240	92	70	117	85	20	22	189	24	98	8	171	7
s	5	6	3	4	2	2	2	6	2	2	1	12	3
n	13	13	13	13	13	13	13	13	11	13	13	13	13
W-1 a	100%	99%	90%	94%	99%	75%	95%	99%	96%	93%	85%	93%	87%
9-2 m	43	13	2	17	85	24	166	477	11	292	10	1865	27
s	3	3	2	1	2	1	2	7	2	3	1	30	2
n	10	10	10	10	10	10	10	10	11	10	10	10	10
G-2 a	74%	56%	34%	45%	100%	96%	98%	99%	92%	97%	71%	99%	93%
GSP-1m	60	13	8	38	102	24	252	237	25	471	21	1288	56
s	5	2	4	2	2	2	3	5	2	2	2	13	4
n	6	6	6	6	6	6	6	6	11	6	6	6	6
GSP-1a	78%	100%	89%	91%	96%	86%	99%	97%	79%	94%	72%	99%	94%
BCR-1	402	25	11	28	121	22	49	338	36	188	12	740	18
s	4	6	3	1	2	1	2	8	1	1	3	10	4
n	6	6	6	6	6	6	6	6	11	6	6	6	1
BCR-1a	98%	44%	85%	53%	99%	96%	96%	98%	97%	98%	86%	91%	80%
AGV-1	129	12	13	64	87	23	70	687	22	233	12	1218	37
s	5	3	3	2	2	2	3	11	1	3	1	27	5
n	10	10	10	10	10	10	10	10	11	10	10	10	10
AGV-1 a	97%	100%	77%	98%	96%	85%	96%	96%	85%	94%	80%	98%	97%

6. Instrumental Neutron Activation Analysis (INAA)

The technique employed in this study (INAA) has been described in detail by Gordon *et al*. (1968) and reviewed by Pride (1978) therefore only accuracy and precision values as reported by Pride (1978) will be given. The precision is best for the elements La, Sm, Ce and Eu (± 7, ±7, ±11 and ±12% respectively) followed by Tb and Lu (± 14%). Yb shows the poorest precision of all the REE determined (± 18%). These precision values were determined on the basis of replicate analysis of AGV-1. Precision for Nd is not reported since the Nd values were not determined by Pride (Muecke, 1980, personal communication). Accuracy values are given in Table B-2.

Table B-2 (after Pride, 1o78)

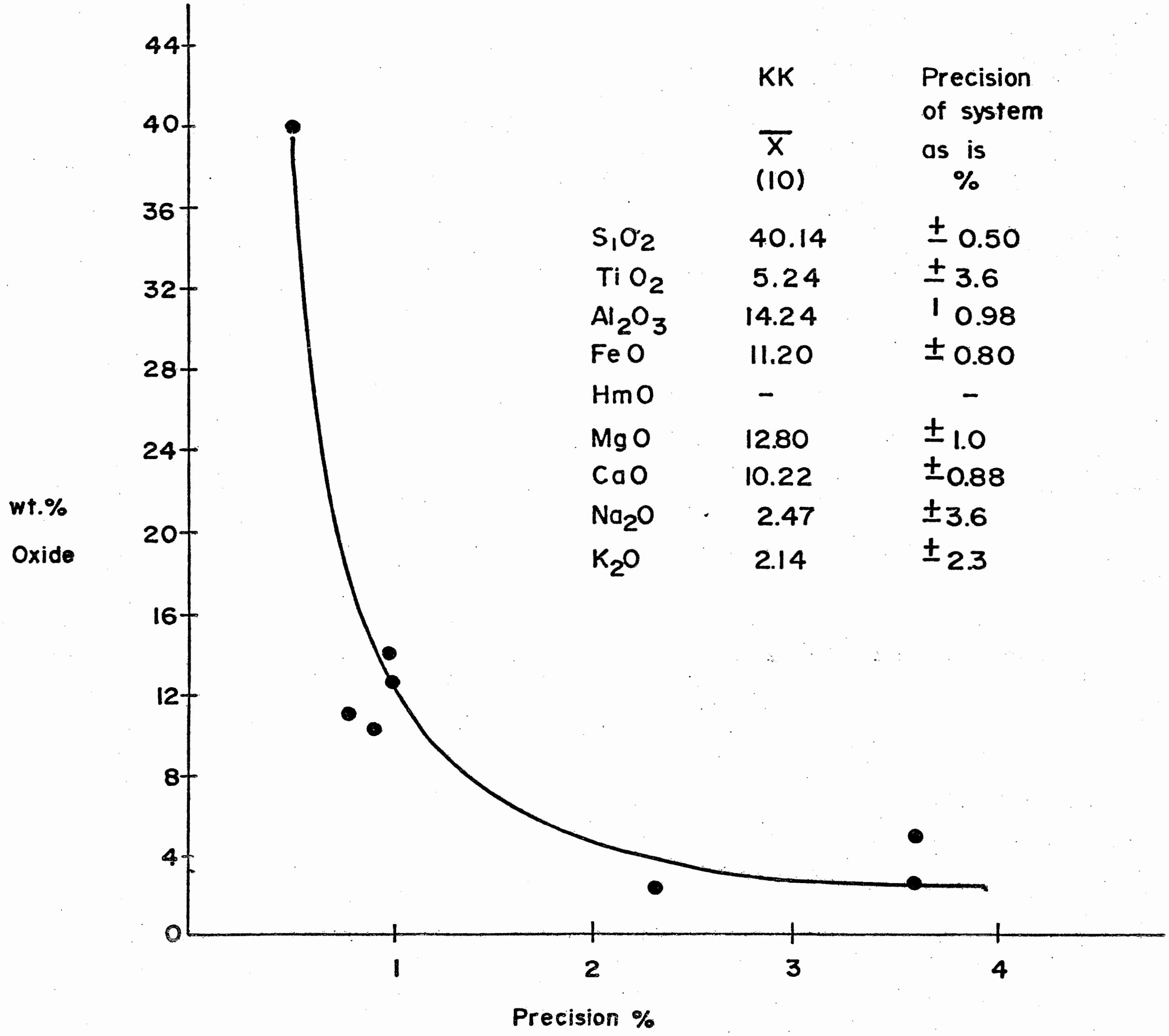
Element	Accuracy
La	± 7 to 10%
Ce	± 11 to 12%
Sm	± 7 to 11%
Eu	± 12 to 20%
Tb	± 14 to 25%
Yb	± 18 to 30%
Lu	± 14 to 19%

7. Electron Microprobe

The electron microprobe at Dalhousie University was used to analyse polished thin sections for both the North Mountain samples and the Mobil-Gulf samples.

Precision (reproducability) is a function of the count rate. The count rate is a function of concentration. The graph on the following page shows approximately what the precision will be for any element (oxide) concentration.

E.D.S. ANALYSIS



	KK $\overline{X}$ (10)	Precision of system as is %
SiO_2	40.14	± 0.50
TiO_2	5.24	± 3.6
Al_2O_3	14.24	± 0.98
FeO	11.20	± 0.80
HmO	–	–
MgO	12.80	± 1.0
CaO	10.22	± 0.88
Na_2O	2.47	± 3.6
K_2O	2.14	± 2.3

APPENDIX C

APPENDIX C

CORE LOGS

Mobil-Gulf Chinampas N-37

Depth (m)	Description
484.6 - 530.4	Sandstone (?) gray-green, very fine grained, hard, siliceous, recrystallized, possibly some basalt with about 10% black basalt below 527.3 m.
530.4 - 536.4	Basalt, black, very fine to cryptocrystalline, with green crystalline inclusions.
536.4 - 542.5	Sandstone, gray-brown, some purplish, very quartzitic, hard, consists of very fine quartz crystals with some volcanic clastics and some basalt matrix.
542.5 - 548.6	Basalt, black with streaks of sandstone, as above.
548.6 - 554.7	Basalt, black with abundant sandstone, as above.
554.7 - 566.9	Quartzite, gray to green-gray, composed of very fine to fine quartz crystals and possibly quartz grains, Basaltic, trace gypsum.

566.9 - 576.1	Quartzite, light gray, salt and pepper, clear to white, fine crystals of quartz with some basalt inclusions, hard, trace gypsum.
576.1 - 585.2	Quartzite, gray, very fine to medium crystals of quartz with trace of gypsum and some basalt inclusions. About 90% quartz.
585.2 - 588.3	Basalt, gray, dull, weathered (?), with some very fine quartz crystals.
588.3 - 603.5	Quartzite, light gray-green, some light red, friable, breaks into powder of very fine to fine crystals, no sedimentary structure
603.5 - 606.6	Quartzite (?), light green gray, salt and pepper, some large crystals which are possibly orthoclase and plagioclase, trace red and green shale inclusions.
606.6 - 622.4	Basalt, gray to green-gray, fine crystalline, hard, with plagioclase, orthoclase, magnetite, green crystals (prehnite?) and some quartz crystals.
622.4 - 627.8	Conventionally cored.
627.8 - 631.9	Cored. No recovery.

627.8 - 643.1	Basalt, red, minor gray-green, fine crystalline, trace vesicles with crystal lining .
643.1 - 649.2	Basalt, as above, becoming more gray.
649.2 - 704.1	Basalt, gray-green, minor red as above, trace talc and minor white crystals (stilbite?).
704.1 - 707.1	Basalt, increasingly red in colour, very fine crystalline, dense.
707.1 - 716.3	Basalt, as above, mainly red, with loose crystals, white stilbite and abundant blue green prehnite (?) in vesicles.
716.3 - 719.3	Basalt, gray green, very fine crystalline, trace white crystals as above.
719.3 - 746.8	Basalt, as above, trace stilbite (?).
746.8 - 749.8	Basalt, as above, with minor red basalt.
749.8 - 774.2	Basalt, gray-green, very fine crystalline, hard, dense.
774.2 - 780.3	Basalt, as above, minor red, vesicular
780.3 - 783.3	Basalt, gray-green, very fine crystalline, hard, dense .
783.3 - 786.4	Basalt, as above, with 40% siltstone, brick red, minor white, brittle.

786.4 - 792.5	Siltstone, mainly red, as above, a few loose quartz grains. Less than 10% basalt in the 792.5 sample.

Getty, GAV-77-3

Depth (m)	Description
0 - 1.5	Overburden, no core recovery
1.5 - 11.6	Gray, amygdaloidal basalt. Zeolites surrounded by a green mineral (chlorite?) and becoming more 'flattened' with depth. Some patches of a non-descript greenish stain.
11.6 - 14.3	Basalt becoming dark gray to nearly black, no zeolites.
14.3 - 15.8	Basalt, as above but maximum grain size of the flow.
15.8 - 20.3	Basalt, becoming more gray with some amygdules. Lower contact at 20.3 metres.
Flow 16 Flow 15	
20.3 - 22.6	Gray, amygdaloidal basalt. Smallest amygdules in flow top grading down into amygdules up to 2 cm. in diameter.
22.6 - 23.8	Massive, gray, basalt with no amygdules.
23.8 - 24.4	Basalt becoming more reddish. Some small amygdules. Contact at 24.4 metres.
Flow 15 Flow 14	
24.4 - 26.8	Reddish, amygdaloidal basalt.

26.8 - 29.6	Basalt, reddish as above becoming more gray. Amygdules not as abundant and more elongate.
29.6 - 39.6	Gray basalt, amygdules virtually absent.
39.6 - 40.5	Basalt becoming reddish with a few large rounded amygdules. Contact at 40.5 metres.

Flow 14
Flow 13

40.5 - 41.5	Reddish basalt with small, abundant amygdules.
41.5 - 45.1	Gray basalt with a few elongate amygdules.
45.1 - 46.3	Massive gray basalt.
46.3 - 50	Gray basalt with very small white vesicles throughout. Occasional zeolite veins.
50 - 54.6	Gray basalt as above but amygdules filled with green mineral (chlorite?) and sporadic green patches.
54.6 - 56.1	Basalt, fine grained and reddish, small rounded white amygdules. Contact at 56.1 metres.

Flow 13
Flow 12

56.1 - 57.8	Reddish, amygdaloidal basalt.
57.8 - 58.4	Basalt, more grayish, no amygdules.

58.4 - 58.8	Reddish basalt with small amygdules. Brick red, fine grained material at 58.8 metres defines contact.

Flow 12

Flow 11

58.8 - 61.0	Reddish, amygdaloidal basalt with small veins and microfractures common.
61.0 - 65.8	Essentially gray, massive basalt with some thin amygdaloidal horizons.
65.8 - 68.4	Gray and massive as above with small greenish alteration patches (chlorophaeite?)
68.4 - 68.7	Reddish, amygdaloidal basalt. Contact at 68.7 metres.
68.7 - 69.5	Reddish basalt with amygdules decreasing in size downward.
69.5 - 75.3	Gray, massive basalt with scattered amygdules.
75.3 - 77.4	Massive, gray basalt.
77.4 - 78.5	Gray, with small irregularly shaped amygdules.
78.5 - 80.5	Massive, gray basalt.
80.5 - 80.9	Reddish basalt with a few amygdules. Contact at 80.9 metres.

Flow 10

Flow 9

80.9 - 81.7	Reddish, amygdaloidal zone

81.7 - 84.3	Amygdaloidal with amygdules less abundant and becoming less red.
84.3 - 89.9	Essentially massive, gray basalt. Small green amygdules becoming more prominent at 86.4 metres.
89.9 - 91.7	Gray and massive.
91.7 - 92.2	Red and amygdaloidal. Contact at 92.2 metres.

Flow 9
Flow 8

92.2 - 94.3	Alternating red and gray amygdaloidal basalt.
94.3 - 98.5	Amygdaloidal basalt going from reddish to light gray then dark gray.
98.5 - 105.5	Essentially massive, dark gray basalt with a zeolite pipe from 103 - 103.9 metres.
105.5 - 106	Increasingly red and amygdaloidal to contact at 106 metres.

Flow 8
Flow 7

106 - 107.7	Amygdaloidal, red basalt becoming more gray.
107.7 - 113.7	Gray, amygdaloidal basalt with occasional zeolite veins.

113.7 - 117	Essentially massive, gray basalt with small, irregular, white amygdules.
117 - 120.2	Massive, gray basalt with a hematized vein at 120 metres.
120.2 - 121.0	Red amygdaloidal basalt. A possible auto intruded flow top at 120.5 metres. Contact is apparently at 121.0 metres.

Flow 7
Flow 6

121.0 - 122.5	Red, amygdaloidal basalt.
122.5 - 123.1	Massive, very red, friable basalt.
123.1 - 123.4	Red, amygdaloidal basalt.
123.4 - 125.3	Reddish to purplish, massive basalt with thin amygdaloidal horizons (auto-intruded flow tops?) Contact apparently at 125.3 metres.

Flow 6
Flow 5

125.3 - 126.2	Red amygdaloidal basalt.
126 - 127.6	Dark gray, massive basalt.
127.6 - 128.0	Red, amygdaloidal basalt. Contact at 128 metres.

Flow 5
Flow 4

128.0 - 128.9	Red, amygdaloidal basalt.

128.9 - 137.5	Essentially massive, gray basalt. A few isolated amygdules at 131.7 metres. Green amygdules prominent from 132.3 - 133.5 metres.
137.5 - 137.8	Red, amygdaloidal basalt. The contact at 137.8 metres is very fine grained and brick red. May possibly be remnant interflow sediments.

Flow 4
Flow 3

137.8 - 140.8	Red and amygdaloidal basalt with thin massive bands.
140.8 - 142.5	Slightly purplish, massive basalt.
142.5 - 143.3	Red and amygdaloidal to contact at 143.3 metres.

Flow 3
Flow 2

143.3 - 143.7	Red and amygdaloidal basalt.
143.7 - 147.2	Gray, amygdaloidal basalt.
147.2 - 151.2	Massive, gray basalt.
151.2 - 152.7	Purplish basalt, becoming more reddish and amygdaloidal. Thin light gray, altered band at 151.5 metres. Apparent contact is at 152.7 metres.

Flow 2

Flow 1

152.7 - 157.9	Rather red, amygdaloidal basalt
157.9 - 160.3	Purplish basalt with amygdules decreasing in size. Becoming greenish.
160.3 - 210.2	White amygdules virtually absent from here to within 0.5 metres of the basal contact. Essentially massive basalt with a spotty appearence. These spots are greenish alteration patches (chlorite?). Colour varies from greenish gray to light gray or dark gray. The greenish sections have more of the alteration patches. Small chloritized fractures abundant throughout the flow.

Flow 1

Blomidon Shale