A Comparative Petrological Study of

Three Nova Scotian Intrusions: the

Jeddore Dyke, the Sober Island Dyke,

and the Marshdale Intrusive.

by

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Abstract

A thorough investigation of three igneous bodies found in Nova Scotia (Jeddore dyke, Sober Island dyke, and Marshdale plug) has brought out a number of important results. The two dykes, located along the Eastern Shore, are calc-alkaline lamprophyres with ages of 370 ± 5 Ma., approximately contemporaneous with the Musquodoboit and South Mountain batholiths. Their similar mineralogy, age, orientation, and chemistry suggest they are genetically related. The Marshdale plug, on the other hand, is a gabbroic body having few if any similarities to the two dykes. It does, however, share several features with the Shelburne dyke or 'Great Dyke' suggesting that it formed during Triassic rifting associated with the opening of the North Atlantic Ocean.

Acknowledgements

I would like to thank Dr. D.B. Clarke for his supervision and assistance, Dr. A.K. Chatterjee for providing valuable data and ideas, Dr. P. Reynolds for his time in determining the ages of the dykes and explaining the principles of the technique, Dr. J.M Hall and Alan Ruffman for their advice, Bob MacKay for his help in the use of the microprobe, and everyone else who contributed to making this thesis a reality.

Chapter 1: Introduction

1.1 Introduction to Dykes and Dyke Swarms

Dykes are defined as sheet-like intrusions discordant with their host rocks (Thorpe & Brown 1985). In zones of rifting or crustal extension they are good indicators of stress patterns, filling tensional fractures (Halls, 1982). Dykes, and xenoliths found within them, potentially, carry valuable information about the nature of the Earth at depth.

More significant than individual dykes, however, are dyke swarms defined as series of dykes emanating from a common magma chamber (Press & Seiver, 1982). Dyke swarms are indicators of regional stress patterns rather than local stress fields.

Two dykes (the Jeddore dyke and Sober Island dyke), together with another intrusive body (the Marshdale intrusive), are described and compared within this thesis. Objectives of this thesis include determining both the genetic and tectonic affinities of these three intrusions.

1.2 Background of the Eastern North America (ENA) Dyke Swarm and other Related (Mesozoic) Igneous Activity

Widespread basaltic volcanism and intrusion of mafic magmas occurred during the Late Triassic, in many areas of the world including the east coast of North America (May,

1971). This time coincides with a period of breakup of the continents resulting in the formation of the present Atlantic Ocean. Several fractures formed in response to the tensional stress built up immediately prior to, and during, this breakup. These fractures became filled by mafic magmas and now appear as dyke swarms. May (1971) has shown that if the continents surrounding the Atlantic are reassembled in their pre-Triassic positions, then the Mesozoic dykes found today on all these continents will form a radial pattern centered on the Bahamian Platform (Fig. 1.1).

McHone and Butler (1984) divide the Mesozoic igneous rocks of eastern North America into four groups or provinces. They define these provinces on the basis of common ages and neighboring distributions, and only secondarily by membership in a magmatic series. They justify this by pointing out that actual magmatic relationships between igneous bodies are often obscured by factors such as: mode of emplacement, size and shape, style of crystallization, differentiation, contamination, and level of exposure.

The two provinces of interest to this study are the Coastal New England (CNE) province and the Eastern North America (ENA) province, both located along the east coast of North America.   The CNE province is characterized by lamprophyric and porphyritic diabase dykes which intruded

236-212 million years ago during a period of broad domal uplift preceding the Triassic (van Eysinga, 1983) rifting stage (McHone & Butler, 1984). These dykes occur almost exclusively along the coast.

The ENA province includes all the diabase dykes discussed earlier by May (1971) and classified chemically and mineralogically by Weigand and Ragland (1970). The age of magmatism of the ENA province is from 190 to 170 million years ago. The Shelburne dyke of southwestern Nova Scotia is thought to belong to this igneous province (Papezik & Barr, 1981). Brief summaries of the geophysical and geochemical investigations of the ENA rocks follow in the next section.

1.2.1 Geophysics of the Eastern North America Dyke Swarm

The regional magnetic poles of the dykes within the swarm are very closely grouped suggesting a common time of emplacement for these dykes (DeBoer, 1967). Paleomagnetic directions (remnent magnetization) suggested a Jurassic age (DeBoer, 1967), but subsequent work, both on inclination distributions and radiometric dating, place the age of the dykes as Triassic (DeBoer & Snider, 1979). There is some variation in the age and distribution of the dykes in the swarm. The dykes to the north (i.e. New England and the Maritimes) are younger and trend in a northeasterly

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direction, whereas dykes to the south (i.e. the Carolinas) are older and trend in a northwesterly direction (DeBoer & Snider 1979, May 1971, Ragland et.al. 1968). The age variation is explained by a gradual opening of the Atlantic Ocean or the "zipper effect" (DeBoer & Snider, 1979). The pre-existing stress pattern (Fig. 1.1) explains the variation in orientations.

1.2.2 Geochemistry of the Eastern North America Dyke Swarm

The mineralogy and texture of the ENA dykes is 40-60% plagioclase (An_{50}-An_{70}), 25-45% augite ($Wo_{35}En_{60}Fs_{5}$-$Wo_{45}En_{45}Fs_{10}$), 0-20% olivine (Fo_{70}-Fo_{85}), 0-10% intergrown quartz and alkali-feldspar, and secondary magnetite, ilmenite and apatite, all in a sub-ophitic texture (Weigand & Ragland, 1970).

Based on their bulk rock chemistry, the dykes of the ENA swarm are further subdivided into three major categories. These categories are:

a) olivine-normative diabase

b) high-TiO_2, quartz-normative diabase

c) low-TiO_2, quartz normative diabase

(Weigand & Ragland, 1970).

These three types of dykes are unequally distributed within the swarm, and there seems to be no correlation between the chemistry of the dykes and tectonic setting, country rock

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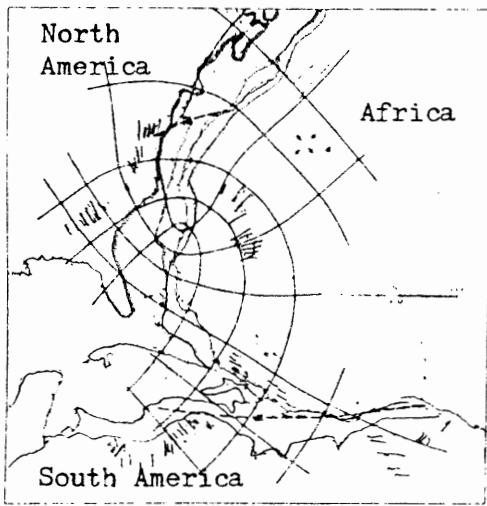
Figure 1.1 : Tensional stress field during the Mesozoic. from (May, 1971)

Trajectories of principal stress indicated by the pattern of Triassic-Jurassic dikes. Lines normal to tensional stress are convex to the south. Lines normal to compressional stress are convex to the north. Heavy dashed lines are possible shear faults.

NEW ENGLAND REGIONAL IGNEOUS EVENTS

NORTH ATLANTIC TECTONIC EVENTS

- Separation of Greenland from Norway

- Opening of Labrador Sea
- Cessation of major fracturing along New England Seamount chain

- Age of ocean crust at eastern end of New England Seamount chain

- Separation of Newfoundland from Ireland

- Separation of Newfoundland from Iberia

- Beginning of rifting between Newfoundland and Iberia

Steady-state spreading of central North Atlantic south of Newfoundland

- Eastward ridge jump

- Separation of eastern North America from northwestern Africa

- Beginning of rifting in eastern North America

- Pre-rifting uplift

Figure 1.2 :

Correlation between North Atlantic tectonic events and New England igneous events after (McHone & Butler, 1984).

NEQ – New England Quebec Province

ENA – Eastern North America Province

CNE – Coastal New England Province

SM – Seamounts

WMMS – White Mountain Magma Series

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chemistry of the dykes and tectonic setting, country rock lithology, or gravity and magnetic anomalies (Weigand & Ragland, 1970). The magma for the olivine-normative type, concentrated towards the south in the Carolinas, encountered open fracture systems permitting rapid ascent. The same magma in the northeastern part of the swarm may have encountered a closed fracture system causing it to accumulate and fractionate thereby becoming quartz-normative.

1.3   Previous Work

The three intrusive bodies examined in this thesis have largely been overlooked or given only brief mention in geological maps and reports of Nova Scotia. Except for a few maps, no published material on any of the three bodies exists. The author is aware, however, of a number of parties actively investigating the Jeddore and Sober Island dykes. These include members of the Nova Scotia Department of Mines and Energy (NSDME), Victor Owen, John Greenough, Charlotte Hy, and Alan Ruffman.

1.3.1   Jeddore Dyke

The Jeddore dyke is the least documented of the three bodies. The most recent geological map of the area is the GSC (Geological Survey of Canada) map by Faribault (1897).

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The dyke is not shown on this map, nor does it appear on more recent, aeromagnetic maps probably because of its small size. There is no mention of this dyke anywhere in the literature, but a manuscript mentioning it has recently been submitted by Ruffman & Greenough (unpublished).

1.3.2   Sober Island Dyke

The most recent map of the Sober Island area is a 1:50,000 scale, GSC map, 1648A (Henderson, 1986). The dyke is shown as a thin line toward the south of Sober Island near a synclinal axis and trending in a northwest-southeast direction. There is a brief caption in the margin stating that the dyke is 2m wide, 1.5km long, undeformed and of unknown age (Henderson, 1986). Ruffman & Greenough (unpublished) also refer to this dyke.

1.3.3   Marshdale Intrusive

This body was not exposed when Benson (1967) mapped the area for the GSC. He did, however, mention the presence of dark green diabase dykes in the area. One is labelled on his map just across the road from the Marshdale intrusive (see next chapter). A more recent map of the Eureka Area (Giles, 1982) shows the intrusion as a gravel pit, but unfortunately this pit is 2km outside the geological portion of the map. On a regional aeromagnetic map (no date), ref. 11-E-7, by

7

Figure 1.3

N

50 km

8

Marshdale
Intrusive

x

Pictou

Colchester

Guysborough

Halifax

Liscomb
Complex

⊗—Sober Island
Dyke

Jeddore
Dyke

Shelburne
Dyke
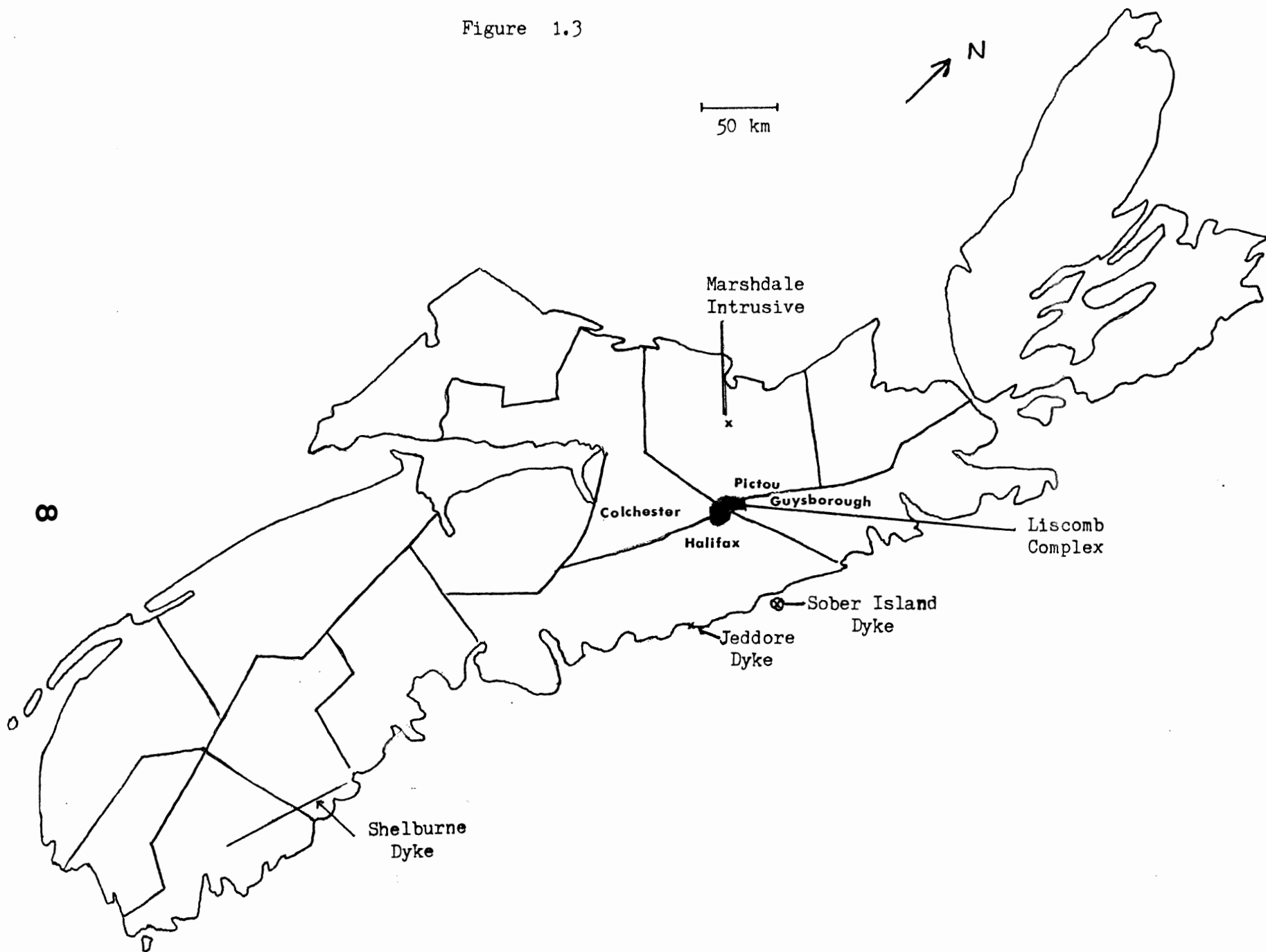
NSDME, the body appears as a circular magnetic anomaly. There is no other literature for this body.

1.4 Approach

The Jeddore dyke, the Sober Island dyke and the Marshdale intrusive will be described and compared using field relationships, petrography, mineral chemistry, bulk rock chemistry, and $^{40}Ar-^{39}Ar$ radiometric dating. Comparisons between the three intrusions and the Shelburne Dyke (Great Dyke) and parts of the Liscomb Complex are made using available literature. The Shelburne dyke is representative of the ENA dyke swarm while the Liscomb Complex is a large intrusive body centrally located with respect to the three intrusions under investigation. Genetic relationships, tectonic settings and petrogenetic models will be discussed for all these igneous bodies.

Chapter 2:   Field Relations

2.1   Introduction

This chapter describes the location, orientation and local geology of the Jeddore dyke, the Sober Island dyke and the Marshdale intrusive.   Comparisons of these three bodies with the Shelburne dyke and the Liscomb Complex are given at the end of this chapter.

Field work for this study was done by the author on August 8, September 7, October 3, and October 12, 1987, and by members of NSDME during the summer of 1986. Dr. Chatterjee at NSDME provided samples,   thin   sections,   and   bulk   rock   chemical   data; complementary sampling, age dating and mineral chemistry data were added by the author.

2.2   Location

The Jeddore and Sober Island dykes are located along the Eastern Shore of Nova Scotia in the Meguma Zone, whereas the Marshdale intrusive is located just south of Stellarton, in Carboniferous Canso Group rocks.   Between them lies the Liscomb Complex, the only substantial mafic pluton in the Meguma Zone (Fig. 1.3).

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2.2.1 Jeddore Dyke

The Jeddore dyke outcrops on both sides of the East Jeddore road, eight kilometers south of the intersection of this road with Highway 7. The two outcrops are about 100m apart, and are aligned in a northwest-southeast direction. On the NTS coordinate system it is located on map 11-D-10 at coordinates 002513, corresponding to Latitude 44° 43'N and Longtitude 62° 59'W.

The outcrop on the west side of the road (i.e. towards Jeddore Harbour) occurs as an isolated rounded hillock 2.5m high. Directly across the road is an outcrop of the Goldenville Formation of the Meguma Group, the contact between them lying beneath the East Jeddore road. The Meguma Group is the host bedrock in the area.

On the landward or eastern side of the road is a larger, more complete outcrop of the dyke. It has well-exposed surfaces both towards the road, and perpendicular to it along a private driveway. The contact between the dyke and the Meguma is exposed near the eastern edge of this outcrop, and samples were taken at various points, along an east-west line, perpendicular to it. Figure 2.1 shows the dimensions, orientation and sample locations from the two Jeddore dyke outcrops.

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Figure 2.1
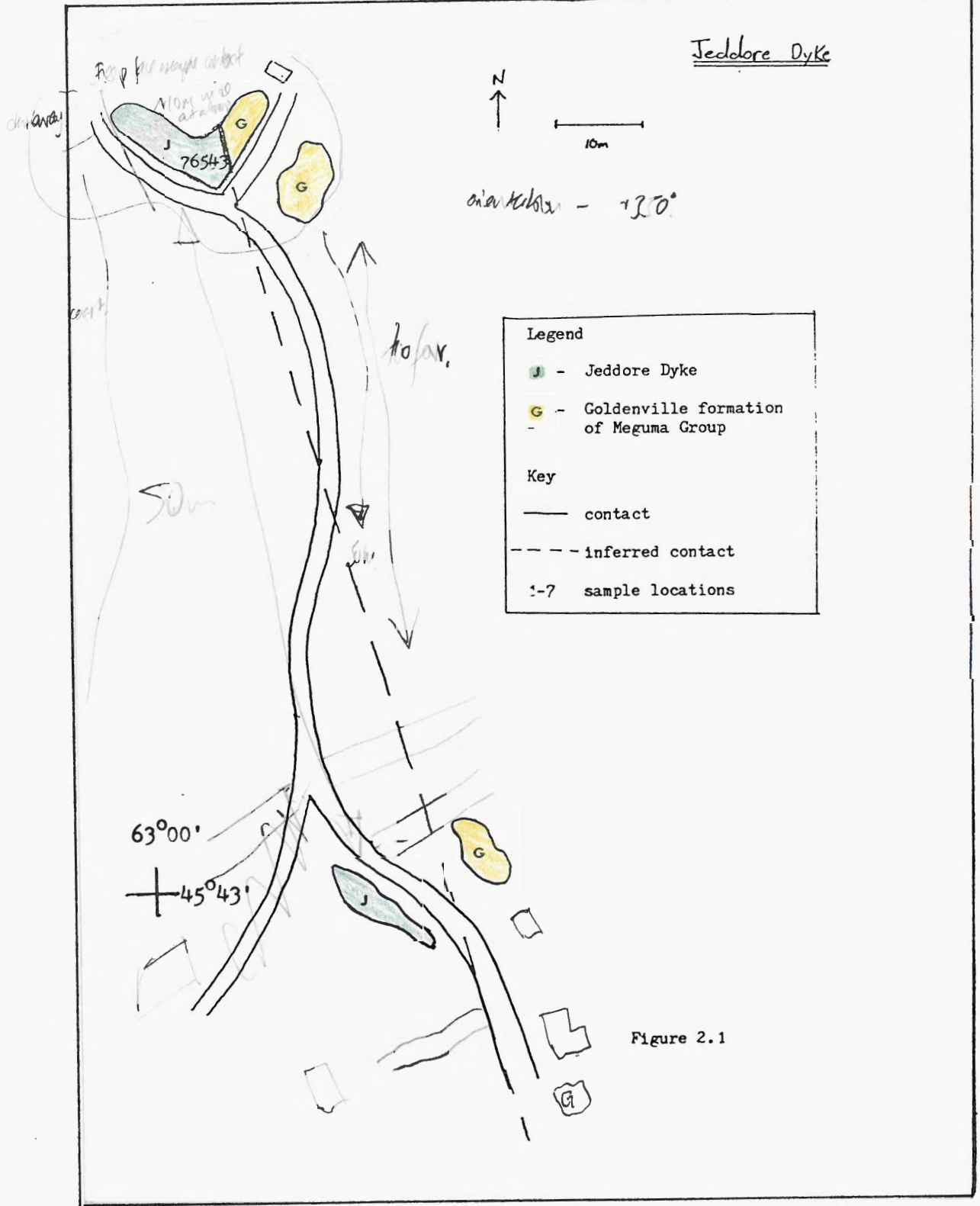
The Jeddore dyke is a medium to dark greenish grey, medium-grained, mafic rock with subhedral to euhedral grains of hornblende, anhedral chlorite, and altered feldspar. The mixture of dark hornblende with light feldspar gives the rock a "spotty" appearance. No other textures are found in either outcrop, except for slight random variations in grain size throughout the dyke and a chilled margin at the contact.

2.2.2   Sober Island Dyke

The Sober Island dyke is located 50km east of the Jeddore dyke, near the town of Sheet Harbour. On the NTS coordinate system it is located on map 11-D-16 at coordinates 427640, corresponding to Latitude 44° 50'N and Longtitude 62° 28'W. The Meguma is again the bedrock in the area. The dyke outcrops in at least four places, on both sides of a small cove (Geddes Cove) located 4.5km from the Sober Island turnoff and 10.8km from the highway 7 junction. The dyke is also seen on the nearest island off the southern coast of Sober Island.

Sample SID-1 was collected from an outcrop situated 60m northwest of the end of the road. This fairly small outcrop (2m square) provided very fresh samples.

Along the shore of Geddes Cove, 65m away from the first outcrop, is another occurrence of the dyke in the form of large boulders which are quite fresh, on strike with the known outcrops

Figure 2.2

Sober Island Dyke

N

10m

Legend
■ - Sober Island Dyke

Key
--- inferred contact
1-3 sample locations

Geddes

Cove

62°28'40"
44°49'52"

2

3
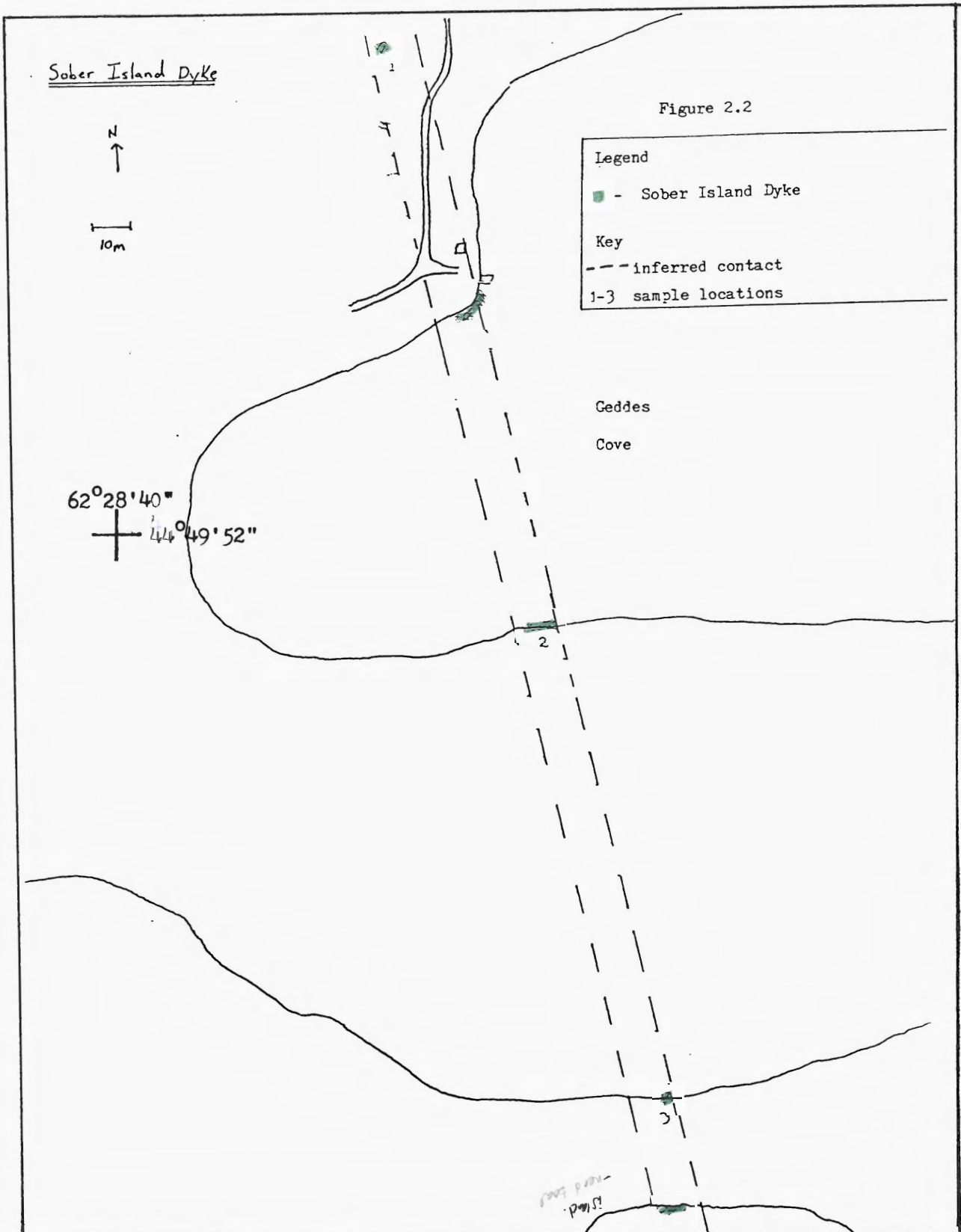
of the dyke, but not in place.

On the southern side of Geddes Cove, continuing in a direction of 160° azimuth and 75m from the boulders, the dyke outcrops agin. Unlike the previous two occurrences, this outcrop is strongly weathered, undoubtedly the result of the effects of seawater at high tide. An east-west dimension of 5m approximates the width of the dyke. Sample SID-2 was taken within 1m of a contact between the dyke and the Meguma, visible on the eastern side of the outcrop. A second much smaller (0.5m wide) appearance of the dyke, having the same orientation as the other outcrops, occurs 2m to the east of the larger outcrop, and probably represents multiple dyke injections or a splay off the main dyke.

The next occurrence of the dyke lies 110m further along the 160° azimuth strike, on the south coast of Sober Island. It is a boulder, 2m wide (E-W), 1m high, 1m long, and in situ. Sample SID-3 was taken from this location.

Several small islands off the coast may also contain parts of the dyke. A 3m wide portion of the dyke has been observed on the closest of these islands. No samples were collected from this island outcrop.

The petrology of the Sober Island dyke is very similar to that of the Jeddore dyke, with hornblende and altered feldspar as

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the dominant mineralogy and an average grain size of about 1mm.
There are no observable textures, and with the exception of
enclaves found in the south coast boulder occurrence, the Sober
Island dyke is a homogeneous body. All occurrences of the dyke
align along a 160° strike suggesting that they all belong to the
same dyke. Figure 2.2 shows the outcrops and sample locations of
the Sober Island dyke.

2.2.3   Marshdale Intrusive

The Marshdale intrusive outcrop is located on the north side
of the road from Hopewell to Glengarry Station, just east of the
junction to Westville.   On the NTS coordinate system it is
located on map 11-E-7 at coordinates 198342, corresponding to
Latitude 45° 27'N and Longtitude 62° 45'W.   The outcrop is a
large 15m high knob with many boulders scattered around its base.
It has recently been quarried for the building of the Pictou
Causeway.

The field relations for the Marshdale intrusive are obscured
by the lack of continuous outcrop and the absence of observable
contacts. This makes the identification of the shape of the body
from field evidence alone unwise.   Although there are no clear
contacts, one is thought to exist where a greenish mylonitic-
looking rock appears (samples MD-1, MD-2).   The other Marshdale
samples were collected along an east-west line, approximately
across the body (Fig. 2.3).

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Marshdale
Intrusive

N ↑

10m

Legend

M - gabbroic plug
    (Marshdale Intrusive)

A - greenish contact zone
    (see text)

C - Carboniferous Canso Group
    host rock

⬡ - gabbroic boulders

Key

1-7 sample locations

1 A 2

M
3 4 5 6 7

M

M

C

62°44'48"
45°25'45"

to
Hopewell

◣ - Dyke recorded by Benson (1967)

to
Westville

to
Glengarry Stn.
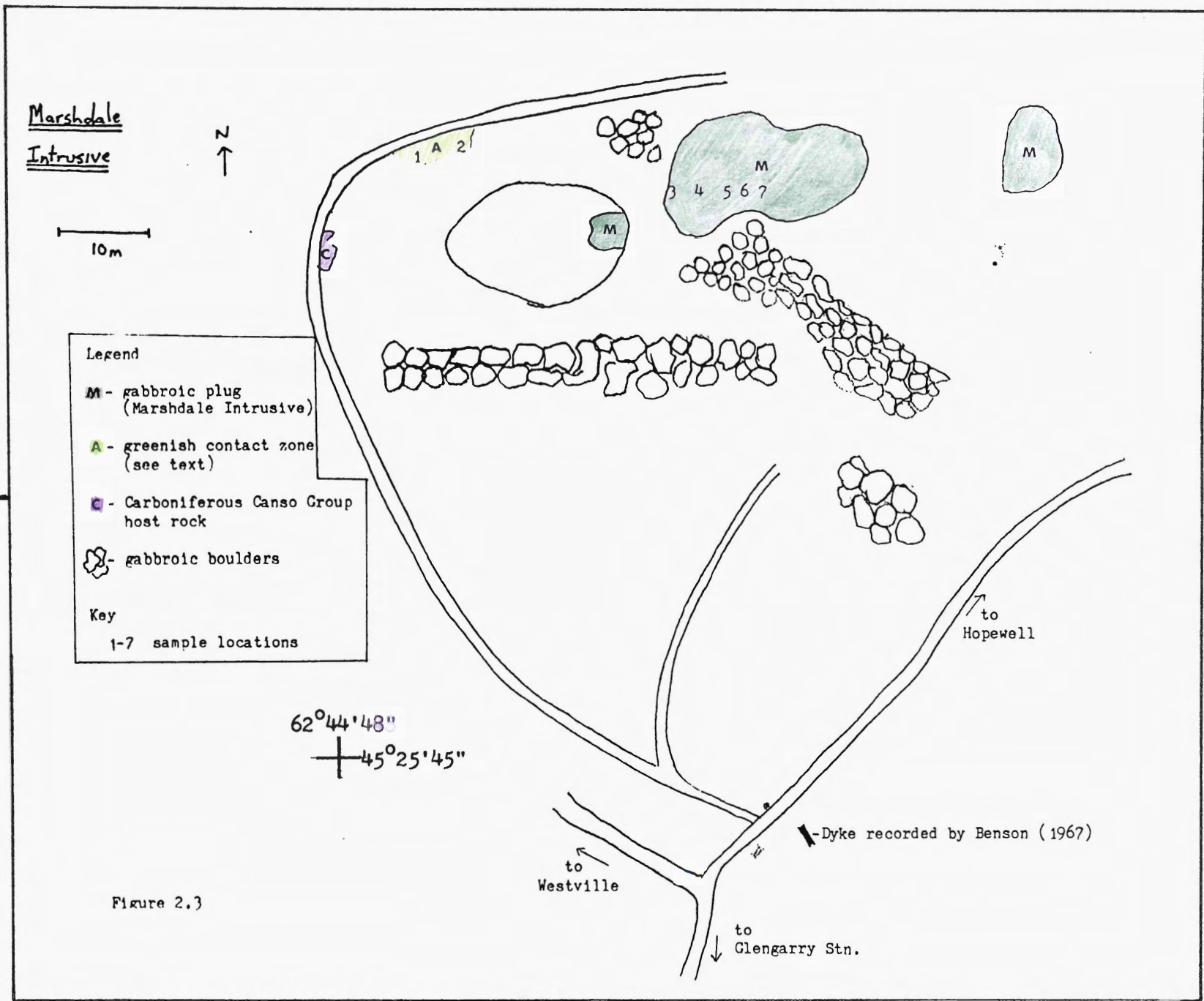
Figure 2.3

The mineralogy of the Marshdale intrusive is unlike that of the eastern shore dykes, containing a wide variety of minerals such as: plagioclase, clinopyroxene, actinolite, epidote, chlorite, pyrite, chalcopyrite, magnetite, ilmenite, apatite, and rutile. Most of these can be identified in hand sample. Other minerals in the immediate area, occurring as veins or as alteration products, include: biotite, quartz, calcite, galena, gypsum, and alkali-feldspar. The main minerals in the outcrop are: plagioclase (60%), clinopyroxene (15%), and opaques (5%).

At the western edge edge of the body is a green mylonitic-looking rock consisting of chlorite, apatite, alkali-feldspar and plagioclase. Parts of this zone are simply mixtures of these minerals, with no observable grains and streaky textures. Elsewhere in this zone, bands of alkali-feldspar define a foliation. Some of the many minerals identified at Marshdale, such as galena and biotite, are found only near this zone, suggesting that the process responsible for the greenish zone is also responsible for the occurrence of these minerals. The appearance of this greenish rock, together with its location relative to the intrusive body, suggests that the edge of the body may have been a fault or shear zone, and that the greenish zone represents the contact between the Marshdale intrusive and the Carboniferous Canso Group host rocks. An alternative hypothesis is that the zone represents a zone of Canso Group sediments that partially melted and recrystallized when they were intruded.

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Within the outcrop are a number of small veins of various types including: gypsum, calcite, epidote, pegmatite, granite, and quartz veins. The abundance and variety of these small veins suggest a more complicated history for this body compared with the two eastern shore dykes.

2.3   Liscomb Complex and Shelburne Dyke

The Liscomb Complex, located between the Marshdale intrusive and the eastern shore dykes, is a horseshoe-shaped group of plutons extending from Pictou and Colchester counties into Halifax and Guysborough counties (Fig. 1.3). Giles and Chatterjee (1986) describe the lithology and dimensions of these plutons. Of particular interest for this thesis are the gabbroic breccia pipes, associated with the complex, known as the Bog Island Lake and the Ten Mile Lake intrusives.

The Shelburne dyke, or Great Dyke as it is commonly called, is a well documented, Triassic, diabase dyke found along the south-eastern shore of Nova Scotia. Many believe it belongs to a much larger system of dykes (the ENA swarm), which formed as a result of the opening of the Atlantic Ocean (Papezik & Barr, 1981). The Shelburne dyke strikes approximately perpendicular to the Jeddore and Sober Island dykes, and, unlike those two dykes, it contains pyroxene rather than hornblende as the main mafic mineral, making the Shelburne dyke more similar to the Marshdale

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intrusive.

2.4   Comparisons

     With five   igneous bodies   under consideration several
comparisons can be made.   On the field scale they are as follows:

Location:

               1.   The Shelburne dyke is several hundreds of
               kilometers   away   from   the Liscomb Complex and
               the other bodies, although according to Ruffman
               (pers. com.), it may lie just off the eastern
               shore.

               2.   The Marshdale intrusive is situated north
               of the great Chedabucto (Glooscap) fault which
               divides Nova Scotia into two distinct regions.
               The other four bodies are located south of this
               fault.

               3.   The Liscomb Complex is centrally positioned
               with respect to the three intrusions under
               investigation.

Orientation: The Jeddore and Sober Island dykes have strikes
               close to 160° Az., i.e. perpendicular to the
               strike of the Shelburne dyke.

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Dimensions: The   width   of   each   dyke   could   only be
                approximated but both   are   around 2-8m.   The
                Shelburne   dyke   is   considerably   larger   with
                estimates ranging up to   180m.   The Marshdale
                intrusive   has   a   diameter   of   at   least 15m;
                absence   of   exposed   contacts   makes   a   more
                accurate measurement impossible.

Geology: The Jeddore and   Sober Island dykes   have   the
                same mineralogy.   The   Marshdale intrusive has
                very   different   mineralogy,   is   much   less
                altered,   and   has   a   much   greater variety of
                minerals   (magnetite,   ilmenite,   epidote,
                olivine,   etc.).   The   Shelburne dyke is most
                like   the   Marshdale   intrusive   with   pyroxene
                instead of amphibole as the main mafic mineral.
                The Marshdale intrusive is   unique   in   that it
                crosscuts Carboniferous Canso Group sedimentary
                rock   while   the   other   three   crosscut   the
                metasedimentary, Cambro-Ordovician, Goldenville
                Formation of the Meguma Group.

2.5   Conclusions

    The following preliminary conclusions can be   made from field
observations:

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1. The Jeddore and Sober Island dykes are the only two bodies of the five with sufficiently similar mineralogy and appearance to possibly have had a similar origin and history.

2. The differences between each of the other igneous bodies are considerable, meaning that complex models or processes are required if they all have a common origin.

Chapter 3:   Petrography

3.1   Introduction

The petrography of the Jeddore dyke, Sober Island dyke, and the Marshdale intrusive are considered in this chapter. Descriptions of the general features found within each body are given in the following sections, with comparisons and conclusions given at the end of the Chapter.

3.1.1   Jeddore Dyke

Nine thin sections from the five samples collected from the Jeddore dyke, and two sections from the metamorphosed Meguma host rock, form the basis for this Section.

The Meguma host rock has been thermally metamorphosed to a hornfels, rich in modal quartz (45-60%). This quartz appears as medium-grained, subhedral porphyroblasts within a matrix of altered feldspar. Hornblende and sphene are also present in small amounts (<2%).   The amount of hornblende is slightly greater in the sample nearer the dyke suggesting an interaction of the dyke with the host rock.

The main mineral in the dyke is seriate porphyritic hornblende, forming approximately 50% of the rock.   These hornblendes range in size from less than 0.3mm to 4mm, are

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generally subhedral in shape, and have greenish-yellow rims enclosing greenish-brown cores. Most of the hornblendes have small inclusions of plagioclase, are enclosed by chlorite, and all are in a matrix of chlorite, quartz and altered feldspar. The amphibole of the sample nearest the contact is not really hornblende but rather secondary actinolite. Other minerals include minute (<0.1mm), randomly distributed opaques and carbonates. As well as existing in the matrix, quartz is also found as very small stringers. None of the minerals in the Jeddore dyke shows deformation. The estimated average modal percentages for the Jeddore dyke are:

hornblende	50%
altered feldspar	28%
chlorite	15%
quartz	5%
opaques	1%
carbonate	1%

Two variations noticeable across the width of the dyke are: 1) chlorite alteration of the hornblende increases from the contact to the center of the dyke; and 2) the hornblendes nearest the contact are small euhedral grains, but those closer to the center of the dyke are anhedral and significantly larger. Possible explanations for these variations are:

a) hydrothermal fluids coming up fractures found only at the center of the dyke.

b) hornblende in the center of the dyke may have been exposed to the atmosphere longer and therefore subjected to more deuteric alteration.

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c) slower cooling at the center of the dyke resulted in the larger grains, while the presence of late deuteric fluids caused the alteration.

The are no significant variations in modal percentages across the width of the dyke.

3.1.2   Sober Island Dyke

The most abundant mineral in the Sober Island dyke is again seriate porphyritic hornblende forming about 40% of the rock. The shape of these hornblendes ranges from euhedral to anhedral in the same thin section, and their colour is greenish-brown with greenish-yellow rims. All the hornblende is porphyritic with grain sizes ranging from 0.2mm to 3.5mm. Up to 30% of the hornblende contains small inclusions of plagioclase and quartz, and most of the hornblende is surrounded by chlorite. The other minerals in the rock form the groundmass and include feldspar, quartz and pyrite. The estimated average modal percentages for the minerals within the Sober Island dyke are:

hornblende	40%
altered plagioclase	25%
chlorite	20%
altered k-feldspar	8%
quartz	5%
pyrite	2%

3.1.3   Marshdale Intrusive

Of the seven samples collected, five are of the intrusive

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and the other two are of the greenish zone adjacent to the body.
The latter two samples are mixtures of green and whitish material
with no observable grain boundaries and a streaky texture.
Microprobe work has revealed that this zone is a mixture of
chlorite, altered feldspar and apatite.

The two samples (MD-3,MD-4) of the dyke closest to the
above-mentioned zone, and the two furthest away (MD-6,MD-7),
consist of 50-65% subhedral to euhedral, twinned, and randomly-
oriented plagioclase laths ranging in size from 0.5mm to 3mm and
having a cumulate texture. The other minerals in the rock occur
between the plagioclase laths as intercumulus phases. The most
abundant of these remaining minerals is augite which forms 10-15%
of the rock, and is being replaced by amphibole. Other minerals
found within these samples include amphibole, olivine, opaques
(ilmenite, magnetite, rutile, pyrite and chalcopyrite), biotite,
epidote, sphene, and apatite.   The range of estimated modal
compositions of the Marshdale intrusive is:

plagioclase	50-65%
augite	10-15%
amphibole	5-10%
opaques	5-10%
olivine	2- 5%
chlorite	2- 5%
epidote	2%
apatite	1%
sphene	1%
biotite	1%

Sample MD-5 is unlike the other samples: it is more
strongly altered; has very little augite (<5%); has more
amphibole (>10%); and the plagioclase is anhedral, rarely

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twinned, altered, and less abundant. More differences with sample MD-5 are found in subsequent chapters of this thesis.

3.1.4 Shelburne Dyke

The Shelburne dyke is a coarse-grained rock of plagioclase (labradorite), and clinopyroxene (augite) in intergranular to subophitic texture (Papezik & Barr, 1981). Opaque minerals form up to 10% of the rock with chlorite, amphibole, and biotite present as alteration products of the pyroxenes.

Lawrence (1966) gives a detailed description of the Shelburne dyke, and gives the following modal analysis for it:

```
plagioclase (An_{63}-An_{75})                          55%
pyroxene (opx & cpx)                                   30%
k-feldspar & quartz (intergrowth)                      10%
other (magnetite, ilmenite, pyrite,olivine,
        apatite, epidote, and chlorite)                 5%
```

On the basis of these modal percentages, the Shelburne dyke has been classified as a quartz diabase (Lawrence, 1966).

3.1.5 Liscomb Complex

The mafic gabbroic pipes known as the Ten Mile Lake (TML) and the Bog Island Lake (BIL) intrusives are the only parts of the Liscomb complex appropriate for comparative purposes. A.K. Chatterjee (NSDME) kindly permitted the author access to thin sections for these bodies so that the brief descriptions following could be made.

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The most abundant mineral in the BIL intrusive is plagioclase followed by biotite and chlorite. Chlorite is found as an alteration product of all the biotites, and some of the pyroxene, in the rock. The dyke also contains large (1.5cm), strongly-fractured, garnet xenocrysts. The modal ranges for the BIL intrusive are:

plagioclase	40-65%
biotite	10-40%
chlorite	10-30%
pyroxene	5-15%
opaques	5-10%
quartz	5-10%

The TML intrusive has even more biotite than the BIL intrusive. The plagioclase of this body is rarely twinned. There is no pyroxene, few opaques, but considerable modal quartz. The modal compositional ranges for the TML intrusive are:

biotite	20-50%
plagioclase	5-30%
quartz	10-15%
chlorite	10-15%

3.2 Comparisons

The Jeddore and Sober Island dykes have very similar mineralogy with porphyritic hornblende forming approximately 50% of each. Most of this hornblende is surrounded by chlorite, and is in a groundmass of quartz, chlorite, and altered feldspar. The only opaques are traces of chromite and pyrite.

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Comparatively, the Marshdale intrusive is primarily cumulate, twinned, euhedral plagioclase with the other minerals found between the laths as intercumulate phases. The Marshdale intrusive also shows a greater mineralogical variety with epidote, apatite, rutile, chalcopyrite, magnetite, ilmenite, and olivine, none of which is found in the other two bodies.

An increase in grain size away from the contact for the Shelburne dyke, discussed by Lawrence (1966), is a variation also observed for the Jeddore dyke. The Shelburne dyke is mineralogically more similar to the Marshdale intrusive than the other two dykes because it contains pyroxene, rather than hornblende as the main mafic mineral, and because it contains up to 10% opaques, many of which are oxides.

The mafic parts of the Liscomb Complex are considerably different from any of the other intrusive bodies; the main differences being the presence of large amounts of biotite and garnet rich xenoliths, both absent in all the other intrusions. Table 3.1 summarizes the comparisons made between the various bodies.

3.3   Conclusions

1.   Mineralogically and texturally the Jeddore and Sober Island dykes are very similar, suggesting a common origin.

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2. The Marshdale intrusive is significantly different from the two eastern shore dykes. These differences include the presence of some minerals (olivine, epidote, ilmenite, magnetite, apatite, biotite and augite), and the absence of other minerals (alkali-feldspar and quartz).

3. The Shelburne dyke and Marshdale intrusive differ from the eastern shore dykes in that they contain pyroxene instead of hornblende as the main mafic mineral. This could be a result of higher crystallization temperatures, drier parental magmas, or both.

4. The Liscomb Complex is unlike any of the other bodies in that biotite is the major mafic mineral and garnet rich xenoliths are contained within it. These two differences suggest that the parental magma for the Liscomb Complex had a significantly different composition from that of the other bodies.

Table 3.1

	Amphibole	Oxides	Plagioclase	Pyroxene	Texture
Jeddore Dyke	50 % Tschermakitic hb to Tschermakite*	trace chromite	40 % andesine *	none	seriate porphyritic
Sober Island Dyke	50 % Tshermakite *	trace chromite	40% andesine *	none	seriate porphyritic
Marshdale Intrusive	5 % Actinolite to Actinolitic hb	10 % titanomagnetite ilmenite	60 % euhedral bytownite	15 % augite	cumulate
Shelburne Dyke	none	5 %	55 % labradorite to bytownite	30 % augite, opx & pigeonite	ophitic
Liscomb Complex	none	5 %	5-40 % not determined	5-15 % augite	not determined

* determined from probe analysis

Chapter 4:   Mineral Chemistry

4.1   Introduction

The oxides and pyroxene of the Marshdale intrusive, and the amphibole and plagioclase of all three intrusions were analyzed using a JEOL-733 superprobe operating at 15Kv and 5nA. Most minerals were analyzed for the purposes of classification, nomenclature and comparison among the three intrusions. The Marshdale oxides were analyzed to get estimates of temperature and oxygen fugacity using the geothermometer of Buddington & Lindsley (1964). Unfortunately, this was the only geothermometer applicable to any of the three bodies.

4.2   Plagioclase

The plagioclase analyses for all three intrusive bodies plus one obtained for the Shelburne dyke are graphically represented in Figure 4.1.

4.2.1   Jeddore Dyke

Seventeen plagioclase grains, randomly selected for analysis, show a wide range in composition (An_{12}-An_{92}); although the majority of analyses fall between An_{25} and An_{65} (see Fig. 4.1). There is no systematic variation in composition across the dyke suggesting that no temperature gradients existed when the

Figure 4.1. Plagioclase (core) analyses
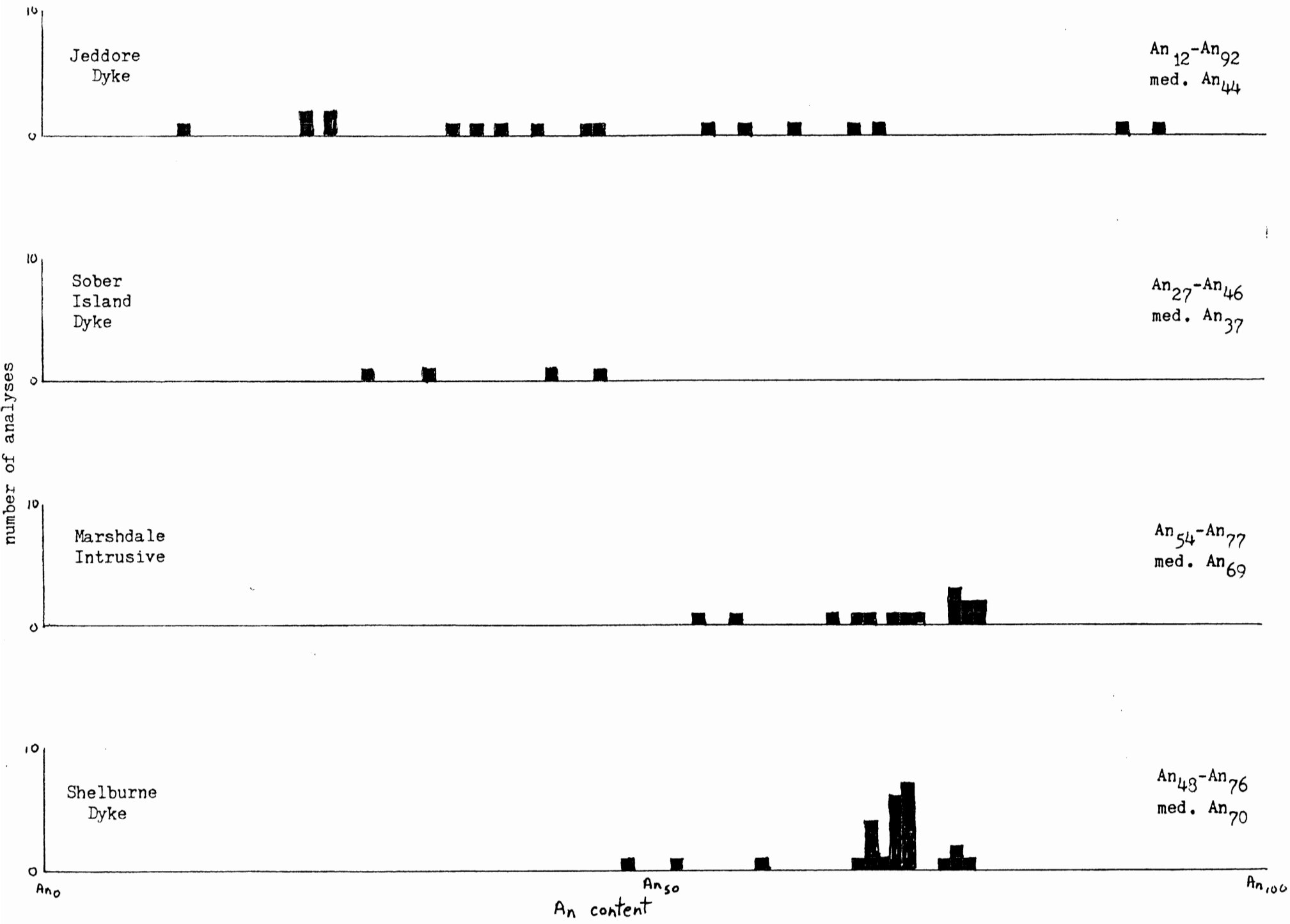
dyke was emplaced.

The plagioclase of the Jeddore dyke is anhedral, small (<1mm), generally strongly altered, and occurs only in the groundmass, meaning that twinning and zoning are optically difficult to detect. Core and rim analysis, however, show a chemical variation between core and rim of 5 to 10 mol% An content, with the cores being more calcic. This means that the plagioclase is normally zoned indicating rapid cooling. The variation of 5% within one grain is considerably less than the total variation within the dyke (80%) and the variation within each thin section (avg. 40%). One explanation is that fluids causing the alteration of the plagioclase did not affect the intrusion in a uniform manner.

4.2.2 Sober Island Dyke

Of the four plagioclase grains analyzed from the one Sober Island dyke thin section, little chemical variation was observed. This may simply reflect the small sample size. Despite this, the results are still useful for comparisons with the other bodies.

The range in An content for the Sober Island dyke plagioclase is $An_{27}-An_{46}$. Optically it is the same as the Jeddore dyke in that twinning and zoning are not apparent. Core-rim analyses, however, show a variation of 12-17mol% An content with the cores being more calcic. This means that the Sober

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Island dyke plagioclase is also normally zoned, and that cooling was even more rapid than it was for the Jeddore dyke. The latter conclusion is consistent with the Sober Island dyke being a smaller body.

4.2.3 Marshdale Intrusive

Eighteen, randomly selected, plagioclase grains show a rather limited range (An_{51}–An_{77}) in composition (Fig. 4.1), making them mostly calcic labradorite and bytownite.

There seems to be a chemical variation within the intrusion with more calcic plagioclase existing towards the center of the body. More analyses are required, however, to make this variation statistically significant. Optical zoning is seen in many of the Marshdale plagioclases. Core-rim analyses, run to determine the extent of this zoning, show a variation of 10–15mol% An content, the core being more calcic. The conclusion again is that the plagioclase is normally zoned and that the Marshdale intrusive cooled quickly.

4.2.4 Liscomb Complex and Shelburne Dyke

Although plagioclase is a major mineral in both the Ten Mile Lake and Bog Island Lake intrusives of the Liscomb Complex, no chemical analyses are available for them.

The analyses of the Shelburne dyke plagioclase, done by Papezik & Barr (1981), show a clustering of An content around An_{70} (Fig. 4.1). The average An content increases 17% from rim to core indicating that the Shelburne dyke plagioclase is also normally zoned.

4.2.5 Comparisons

Plagioclase of the Jeddore and Sober Island dykes is intermediate in composition with andesine being the most common type. Greater variability in An content exists for the Jeddore dyke but this can be attributed to a larger sample size. Plagioclase of the Marshdale intrusive and the Shelburne dyke is much more calcic and less variable than the other two bodies. The plagioclase of all the intrusions is normally zoned suggesting rapid cooling for all of them.

4.3 Amphiboles

Results of some of the amphibole analyses of all three bodies are given in Table 4.1. These and other results are plotted on a classification system of Hawthorne (1981)(Fig. 4.2).

4.3.1 Jeddore Dyke

All amphiboles of the Jeddore dyke fall within the calcic amphibole category (i.e. $(Ca+Na)_B > 1.34$, and $Na < 0.67$). Within
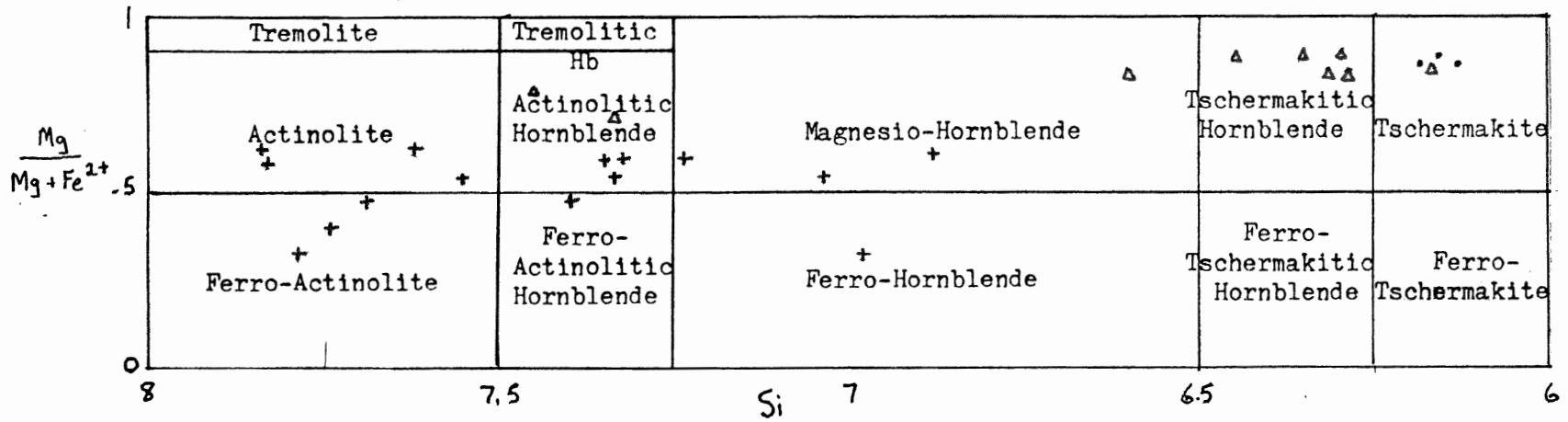
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Table 4.1

Selected Amphibole Analyses

	JD-4	JD-5	JD-7	SID	MD-3	MD-4	MD-5	MD-6
SiO_2	44.79	43.22	46.80	42.44	49.48	52.27	50.34	45.46
TiO_2	1.51	2.64	0.93	2.37	0.74	0.28	0.56	0.29
Al_2O_3	10.70	11.87	10.04	12.02	4.38	3.32	1.52	8.36
Cr_2O_3	0.14	0.25	0.10	0.21	0.14	0.09	0.13	0.12
*FeO	10.64	10.64	13.65	10.76	19.01	15.98	32.08	25.75
MnO	0.19	0.23	0.30	0.22	0.43	0.27	0.48	0.56
MgO	15.17	14.93	14.21	14.84	12.61	14.30	7.40	7.22
CaO	11.35	11.32	11.20	11.10	9.44	10.83	5.41	8.83
Na_2O	1.28	2.38	1.85	2.27	2.01	0.39	0.81	1.59
K_2O	0.51	0.61	0.47	0.62	0.18	0.09	0.19	0.19
	97.16	98.07	99.54	96.83	98.42	97.81	98.91	98.36
Si	6.44	6.16	6.59	6.15	7.33	7.62	7.75	6.96
Al(IV)	1.56	1.84	1.14	1.85	0.67	0.38	0.25	1.04
	8.00	8.00	8.00	8.00	8.00	8.00	8.00	8.00
Al(VI)	0.270	0.210	0.260	0.200	0.094	0.188	0.026	0.470
Ti	0.163	0.294	0.194	0.256	0.081	0.030	0.064	0.032
Cr	0.016	0.016	0.018	0.023	0.016	0.009	0.014	0.014
Fe^{3+}	0.766	0.768	0.956	0.925	---	---	---	---
Mg	3.25	3.23	2.99	3.20	2.78	3.10	1.70	1.65
Fe^{2+}	0.514	0.462	0.582	0.374	2.029	1.673	3.196	2.834
Mn	0.021	0.020	---	0.022	---	---	---	---
	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
Fe^{2+}	---	---	0.072	---	0.331	0.277	0.934	0.466
Mn	0.002	0.001	0.036	0.003	0.053	0.032	0.062	0.071
Ca	1.78	1.74	1.69	1.72	1.50	1.69	0.890	1.45
Na	0.218	0.259	0.202	0.277	0.116	0.001	0.114	0.013
	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Na	0.307	0.388	0.303	0.359	0.459	0.107	0.128	0.459
K	0.092	0.097	0.083	0.113	0.035	0.016	0.037	0.035
	0.399	0.485	0.386	0.472	0.494	0.123	0.165	0.494

* total Fe as FeO

Figure 4.2 after (Hawthorne, 1981)

$(Na + K)_A < 0.50$; $Ti < 0.50$

$(Ca + Na)_B < 1.34$
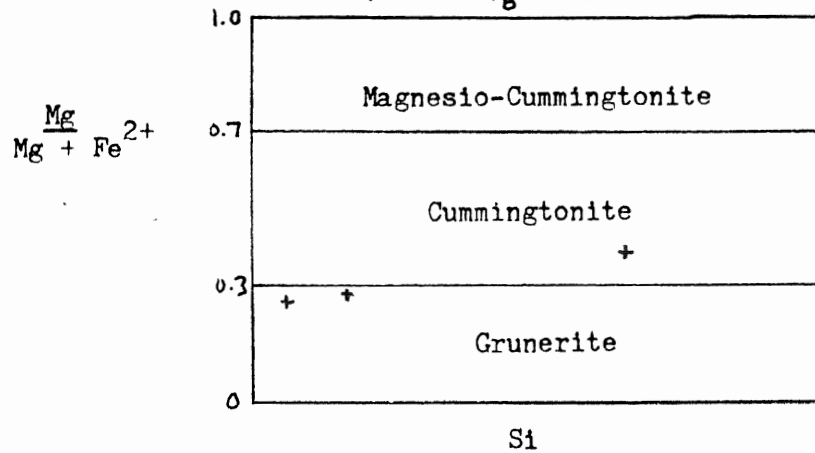
Δ - Jeddore Dyke

• - Sober Island Dyke

+ - Marshdale Intrusive

this category, however, are further subdivisions based on the amount of other elements (Fig. 4.2). There are clearly two main types of amphibole within the Jeddore dyke: first, the primary tschermakitic hornblende and tschermakite of the Jeddore samples, excluding JD-3; and secondly, the secondary actinolitic hornblende of JD-3. A gap exists in Hawthorne's classification scheme between $Fe^{3+} < Al(VI)$ and $Fe^{3+} > Al(tot)$. Five samples lie in this gap and can, therefore, only be classified as calcic amphiboles.

4.3.2   Sober Island Dyke

Only four amphibole grains from the one Sober Island dyke thin section were analyzed and classified. All four are calcic with three of the four classified as tschermakite. The other lies within the gap of the classification scheme and cannot be classified further. The Sober Island dyke contains no secondary actinolite or actinolitic hornblende.

4.3.3   Marshdale Intrusive

The amphiboles of the Marshdale intrusive are all secondary after augite. Most of them are calcic, but three are Fe-Mg amphiboles (i.e. $(Ca+Na)_B < 1.34$). These three, found towards the middle of the body, are characterized by very high iron content. The calcic amphiboles, characterized by high silicon content (>6.88) and intermediate $Mg/(Mg+Fe^{2+})$ ratios (0.49-0.62),

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cover a large range of compositions and consequently have a variety of names (Fig. 4.2).

4.3.4 Liscomb Complex and Shelburne Dyke

Amphibole analyses have not yet been reported for either of these two bodies.

4.3.5 Comparisons

The amphiboles of the Jeddore and Sober Island dykes are all calcic and for the most part primary. In both dykes the amphiboles have high $Mg/(Mg+Fe^{2+})$ ratios and low Si. The amphiboles of the Marshdale intrusive, on the other hand, are entirely secondary replacing augite, and have higher $Mg/(Mg+Fe^{2+})$ ratios and Si values than the other two bodies. The Liscomb Complex and Shelburne dyke have no amphibole at all.

4.4 Pyroxene

The Jeddore and Sober Island dykes do not contain pyroxene and no analyses for the Liscomb Complex are available. Results for the remaining two bodies are presented in Tables 4.3 and 4.4, and are plotted on the pyroxene quadrilateral (Fig. 4.3).

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Table 4.3

Pyroxene Analyses

	MD-3	MD-3	MD-4	MD-4	MD-4	MD-4	MD-6	MD-6
SiO_2	49.55	52.08	51.79	52.20	51.20	52.26	49.81	50.41
TiO_2	1.65	1.10	1.03	1.04	1.25	1.18	1.73	1.48
Al_2O_3	2.96	1.53	1.89	1.63	2.07	1.73	3.34	2.60
Cr_2O_3	0.09	0.11	0.08	0.11	0.09	0.10	0.07	0.10
*FeO	11.05	10.64	10.61	12.53	11.86	10.93	10.85	9.80
MnO	0.22	0.36	0.22	0.42	0.42	0.34	0.19	0.20
MgO	13.93	14.99	15.44	14.38	14.66	15.70	14.21	14.27
CaO	19.54	18.51	19.23	18.41	18.34	18.64	19.26	20.53
Na_2O	0.58	0.60	0.53	0.74	0.66	0.56	0.61	0.68
K_2O	0.03	0.04	0.03	0.06	0.04	0.05	0.03	0.04
	99.59	99.96	100.82	101.51	100.59	101.46	100.11	100.09
Si	1.874	1.945	1.921	1.936	1.914	1.925	1.868	1.889
Al(IV)	0.126	0.055	0.079	0.064	0.086	0.075	0.132	0.111
	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Al(VI)	0.005	0.012	0.003	0.007	0.005	---	0.016	0.004
Ti	0.047	0.031	0.028	0.029	0.035	0.032	0.049	0.041
Cr	0.002	0.003	0.002	0.003	0.002	0.002	0.001	0.002
Mg	0.785	0.825	0.853	0.795	0.816	0.862	0.794	0.797
Fe^{2+}	0.349	0.332	0.329	0.389	0.371	0.337	0.340	0.307
Mn	0.007	0.011	0.007	0.013	0.013	0.010	0.006	0.006
Ca	0.791	0.740	0.764	0.731	0.734	0.736	0.774	0.824
Na	0.042	0.043	0.037	0.053	0.048	0.040	0.044	0.049
K	0.001	0.002	0.001	0.002	0.001	0.001	0.001	0.001
	2.03	2.01	2.02	2.02	2.03	2.02	2.03	2.03
Ca	40.9	38.6	39.1	37.9	38.0	37.8	40.4	42.6
Mg	40.6	43.5	43.7	41.2	42.2	44.3	41.5	41.2
Fe+Mn	18.5	17.9	17.2	20.9	19.8	17.9	18.1	16.2

* total Fe as FeO

	112 Opx Core	112 Opx Rim	112 Cpx Aug	116 Cpx Aug	116 Cpx Pig	120 Aug	SH-1 Aug	SH-1 Opx
SiO_2	54.30	52.23	51.34	51.15	52.75	51.50	52.36	54.65
TiO_2	0.18	0.37	0.70	0.58	0.28	0.31	0.34	0.17
Al_2O_3	1.63	1.16	1.52	2.01	0.91	2.87	1.68	0.88
Cr_2O_3	0.13	0.05	0.18	0.09	0.02	0.40	0.07	0.09
FeO^*	13.61	24.38	11.22	13.30	21.86	8.85	9.27	12.93
MnO	0.25	0.39	0.23	0.23	0.41	0.20	0.20	0.24
MgO	26.75	20.55	15.44	14.59	20.67	18.36	16.96	27.93
CaO	2.43	1.98	18.78	17.55	4.29	15.75	17.28	2.21
Na_2O	0.04	0.03	0.25	0.21	0.08	0.19	0.20	0.01
Total	99.31	101.14	99.65	99.73	101.27	98.43	98.36	99.10
				Ions per 6 oxygens				
Si	1.962	1.950	1.930	1.932	1.958	1.918	1.961	1.973
Al^{iv}	0.038	0.050	0.066	0.068	0.039	0.082	0.039	0.027
Al^{vi}	0.031	—	—	0.020	—	0.043	0.034	0.010
T_i	0.004	0.010	0.019	0.015	0.007	0.007	0.009	0.004
Cr	0.003	0.001	0.004	0.002	—	0.011	0.002	0.002
Mg	1.440	1.143	0.865	0.821	1.143	1.019	0.946	1.502
Fe	0.410	0.760	0.352	0.420	0.678	0.275	0.290	0.390
Mn	0.007	0.012	0.006	0.006	0.012	0.005	0.005	0.006
Ca	0.093	0.079	0.756	0.709	0.169	0.628	0.692	0.084
Na	0.002	0.001	0.018	0.014	0.005	0.013	0.014	—
Ca	4.8	4.0	38.2	36.2	8.4	32.6	35.8	4.2
Mg	73.8	57.3	43.7	42.0	57.1	52.9	48.9	75.8
$Fe + Mn$	21.4	38.2	18.1	21.8	34.5	14.5	15.3	20.0
En (%)	77.5	59.7	---	---	---	---	---	79.1

Note: Microprobe analyses by V. S. Papezik.
*Total Fe as FeO.
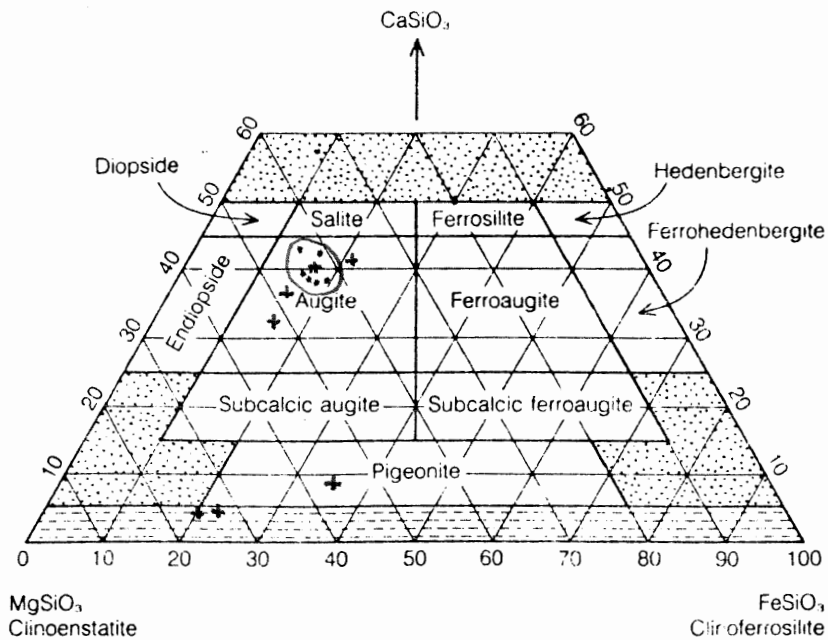
Table 4.4 from (Papezik & Barr, 1981)

Figure 4.3 Pyroxene Quadrilateral after (Berry et. al., 1983)

• - Marshdale Intrusive

+ - Shelburne Dyke

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4.4.1   Marshdale Intrusive

Eight randomly selected pyroxene grains give very consistent results. All eight plot within the augite field of the pyroxene quadrilateral (Fig 4.3); a result consistent with the Marshdale body being a gabbroic plug as discussed in the previous chapter.

4.4.2   Shelburne Dyke

Most of the pyroxenes of the Shelburne dyke also plot within the augite field. The presence of orthopyroxene and pigeonite, however, distinguish it from the other bodies.

4.4.3   Comparisons

The presence of pyroxene in the Marshdale intrusive, Shelburne dyke and Liscomb Complex suggest that these bodies formed from a drier magma, and at a higher temperature, than the eastern shore dykes. The presence of orthopyroxene in the Shelburne dyke indicates that it is silica saturated and may have formed at the highest temperature.

4.5 Oxides

The ilmenite and magnetite of the Marshdale intrusive were analyzed (Table 4.5) so that the Buddington & Lindsley (1964)

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Table 4.5

Oxide   Analyses

Magnetites

	MD-4	MD-4	MD-4	MD-5	MD-6	MD-7	MD-7
SiO_2	---	0.04	0.03	0.09	0.08	0.04	---
TiO_2	7.04	8.58	12.19	17.73	11.48	18.14	13.28
Al_2O_3	2.97	1.40	2.83	0.51	0.42	1.00	0.11
Cr_2O_3	0.75	0.43	1.82	0.06	0.17	1.35	0.62
Fe_2O_3	51.57	50.40	41.04	33.87	46.01	31.31	42.64
FeO	36.53	38.78	41.46	47.18	41.49	47.46	42.66
MnO	0.23	0.27	0.44	0.53	0.31	0.66	0.60
MgO	0.85	0.08	0.15	0.02	0.05	---	0.02
CaO	0.01	---	0.03	---	---	0.03	0.06
	99.95	99.98	99.99	99.99	100.01	99.99	99.99
mol % TiO_2	10	11	16	20	14	21	16
mol % Fe_2O_3	35	33	26	20	29	18	26
mol % FeO	55	56	58	60	57	61	58

Ilmenites

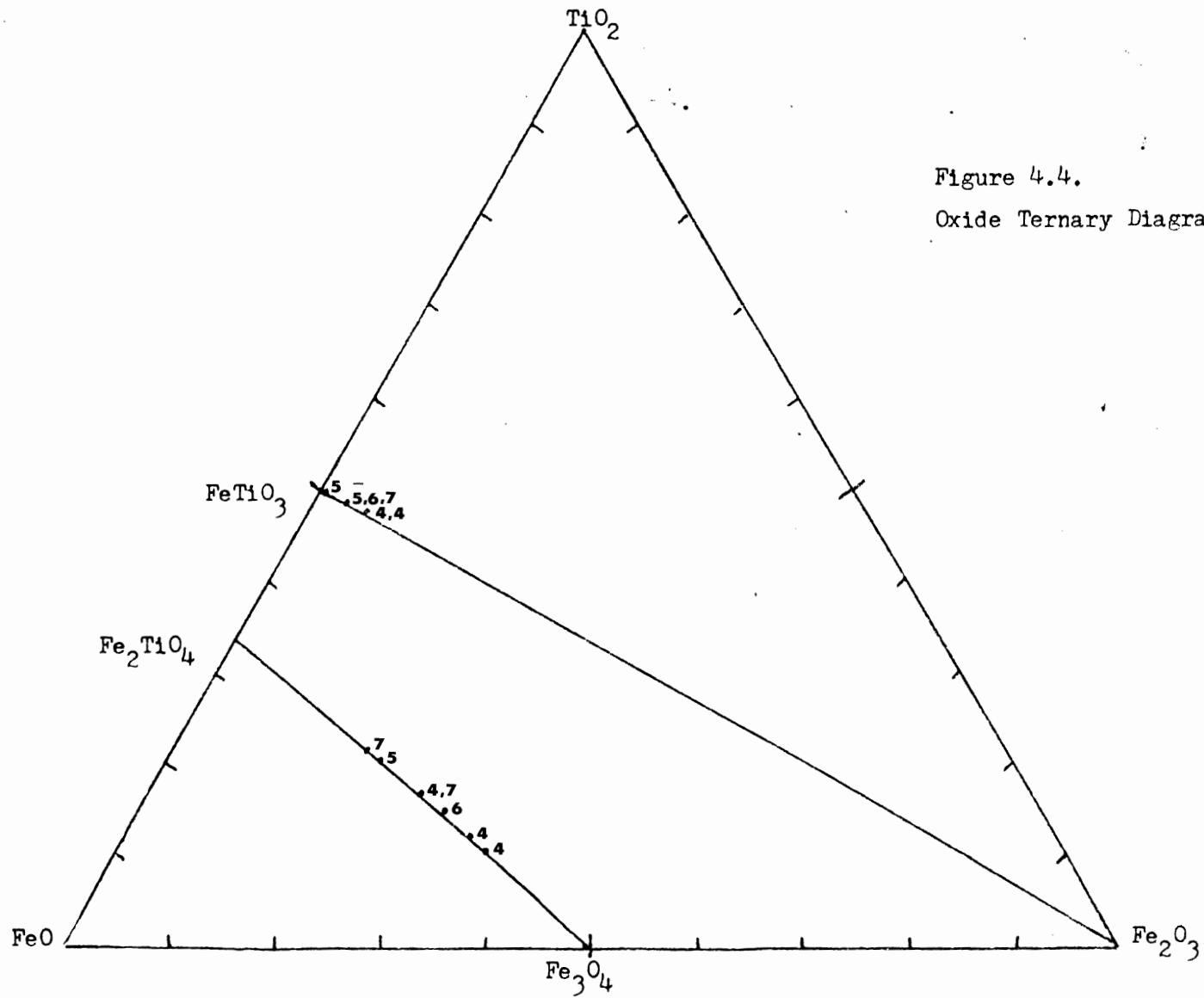|	MD-4	MD-4	MD-5	MD-6	MD-7
SiO_2	---	---	---	---	0.03
TiO_2	47.78	45.57	49.65	48.85	48.37
Al_2O_3	0.02	0.05	0.03	0.05	---
Cr_2O_3	0.04	0.03	---	0.04	0.07
Fe_2O_3	9.35	9.64	5.75	7.33	8.02
FeO	41.54	41.13	43.20	42.53	41.72
MnO	1.11	1.48	1.29	0.96	1.71
MgO	0.15	0.10	0.06	0.23	---
CaO	0.01	---	0.01	0.02	0.08
	100.00	98.00	99.99	100.01	100.00
mol % TiO_2	48	48	49	49	49
mol % Fe_2O_3	5	5	3	4	4
mol % FeO	47	47	48	47	47

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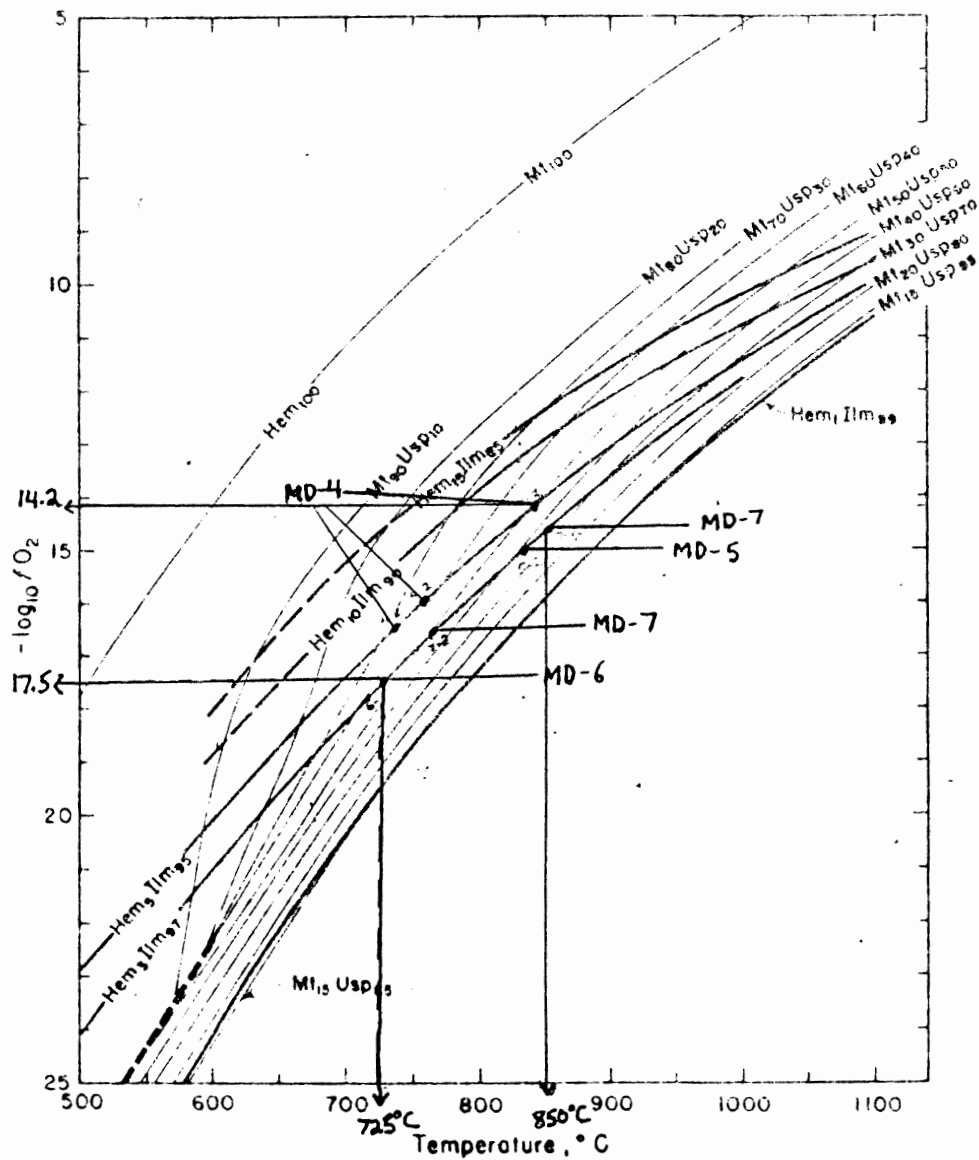Figure 4.4.

Oxide Ternary Diagram

Figure 4.5   Coexisting Oxides Geothermometer
              from (Buddington & Lindsley, 1964)

geothermometer could be used. Figure 4.4 is the ternary diagram
on which the analyses were plotted to determine the hematite-
ilmenite and magnetite-ulvospinel ratios required for the
temperature and oxygen fugacity estimates.

4.5.1   Results

For the seven points used, the temperature estimates range
from a low of 725°C for sample MD-6 to a high of 850°C for sample
MD-7 (Fig. 4.5). The oxygen fugacity estimates range from 3.0 x
10^{-18} atm. for sample MD-6 to 8.0 x 10^{-15} atm. for sample MD-4.

The temperatures obtained using this method are well below
the solidus for mafic rocks and probably represent sub-solidus
exsolution of ilmenite from magmatic titanomagnetite. J.M. Hall
(pers. com., 1988) suggests the following history for the oxide
phases: precipitation from melt, sub-solidus partial exsolution
of the ilmenite lamellae, and hydrothermal alteration which
surrounded some of the oxides with a coating of sphene.

4.6   Conclusions

Two sets of conclusions can be drawn from the evidence
presented in this chapter: first, the naming of each body; and
secondly, estimating the temperature of formation for each body.
These conclusions are based on Figure 4.6, rock type descriptions
by Nockolds et.al. (1978), and the Streckeisen (1976)
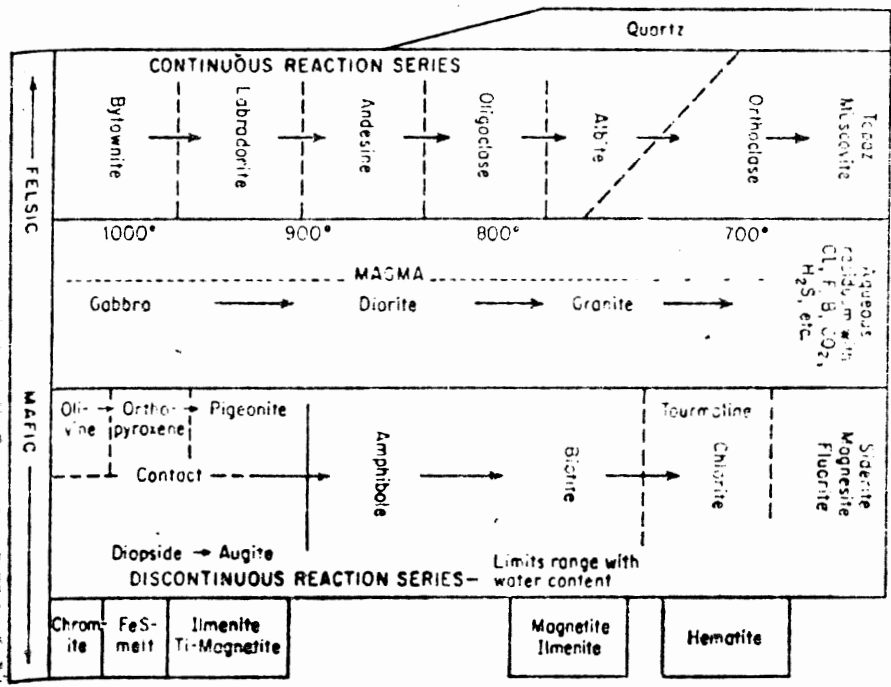
47

Fɪɢ.   The plagioclase sequence in igneous rocks. The approximate order of separation in the normal crystallization of a magma series. (*Modified from Troger and V. M. Goldschmidt.*)

Figure 4.6 from (Kerr, 1977)

classification scheme.

1a)   The   intermediate   An   content   of   the   plagioclase   of   the
      Jeddore and   Sober Island dykes, together with the abundance
      of hornblende and absence of pyroxene, indicate that diorite
      is appropriate rock name for these two bodies.

 b)   The calcic plagioclase   of the Marshdale intrusive, together
      with the presence of augite   and   large   grain   size   of the
      minerals,   suggest   that   gabbro   is an appropriate term for
      this body.

 c)   The   Shelburne dyke differs from the   Marshdale intrusive in
      that   it   contains   orthopyroxene   and the grain size of the
      individual minerals   is smaller.   The   appropriate name for
      this dyke,   therefore   is   a diabase or dolerite, the terms
      used in the literature.

2a)   Using the mineral assemblage of the dykes and Figure 4.6, it
      is   suggested   that   the   Jeddore   and   Sober   Island   dykes
      crystallized between 825°C and 950°C, and that the Marshdale
      intrusive   and   Shelburne   dyke crystallized at temperatures
      greater than 925°C.

 b)   Using the geothermometer of Buddington and   Lindsley (1964),
      a   temperature   range   of   725-850°C   and an oxygen fugacity
      range of 3.0 x 10^{-18} atm. to 8   x 10^{-15} atm. were obtained.
      The   temperature   represents   the sub-solidus temperature at
      which ilmenite exsolved from titanomagnetite.

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Chapter 5:   Bulk Rock Chemistry

5.1   Introduction

A.K. Chatterjee of NSDME provided bulk rock chemical analyses (Table 5.1) for the bodies under investigation.   The author later added two analyses for the Sober Island dyke, and literature values for the Shelburne dyke and Liscomb Complex, to this data base.   Several variation diagrams, including ternary discriminator diagrams and REE plots, were plotted to make comparisons, but not to formulate petrogenetic models or crystal fractionation mechanisms.   The bulk rock data were also used in a calc-alkaline chemical screen proposed by Rock (1984) (Fig. 5.10).

5.1.1   Two-Dimensional Variation Diagrams

Figures 5.1-5.4 show representative combinations of major and trace elements.   In each case the Jeddore and Sober Island dykes form one group, while the Marshdale intrusive forms a distinctly separate one.   The Shelburne dyke, in many cases, plots close to the Marshdale intrusive suggesting a similarity in magma type.   The three parts of the Liscomb Complex are highly variable and cannot be assigned to any of the three intrusions under investigation. The main conclusions drawn from these diagrams are that the Jeddore and Sober Island dykes are chemically similar, if not identical, and that the Marshdale

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Table 5.1

Sample	JD-3	JD-4	JD-5	JD-6	JD-7	SID-1	SID-2	SID-3	MD-3	MD-4	MD-5	MD-6	MD-7	GD-P&B	GD-LAW
Group #	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	3.00	3.00	3.00	3.00	3.00	4.00	4.00
Qual	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Key	1	1	1	1	1	2	2	2	5	5	5	5	5	8	8
Ref	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SiO_2	54.56	55.38	55.17	55.01	53.42	54.28	56.41	53.81	49.36	49.03	50.70	48.86	49.81	53.57	52.72
TiO_2	0.74	0.71	0.66	0.71	0.68	0.83	0.40	0.64	2.21	2.78	3.72	2.92	2.17	1.06	1.07
Al_2O_3	14.90	15.00	14.86	15.37	14.70	16.17	13.70	15.35	17.16	15.18	13.65	15.03	17.14	14.96	15.00
FeO	8.60	7.22	7.23	7.90	7.66	7.74	8.00	8.18	11.49	12.99	14.12	13.27	11.79	9.95	9.83
MnO	0.23	0.18	0.15	0.23	0.15	0.14	0.15	0.15	0.16	0.17	0.20	0.17	0.15	0.17	0.14
MgO	10.76	10.55	10.76	10.59	11.48	9.50	12.01	10.54	6.79	7.48	4.87	6.96	6.82	6.87	6.39
CaO	6.07	6.23	7.20	5.69	7.99	6.88	6.15	7.53	8.99	8.61	7.86	8.97	7.95	10.30	9.84
Na_2O	2.25	2.61	2.35	2.03	2.44	2.76	1.97	2.25	3.49	3.33	4.21	3.41	3.63	2.21	2.63
K_2O	1.77	2.01	1.50	2.37	1.38	1.60	1.12	1.45	0.22	0.27	0.37	0.26	0.43	0.75	2.23
P_2O_5	0.12	0.12	0.13	0.11	0.11	0.11	0.10	0.12	0.14	0.16	0.29	0.16	0.11	0.15	0.14
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	100.00	100.00
Ba	661	835	369	798	323	337	320	392	87	66	152	94	61	207	0
Cr	811	884	843	769	971	526	1222	726	159	150	22	112	157	206	0
Cu	13	28	48	14	21	29	40	79	65	71	100	98	44	113	0
Ga	17	19	14	14	15	14	15	17	20	22	28	26	23	21	0
Nb	7	7	6	6	6	4	4	5	4	6	8	5	4	10	0
Ni	173	198	204	139	209	132	349	248	165	188	29	169	179	78	0
Pb	13	11	8	43	11	5	0	0	5	5	6	4	3	8	0
Rb	57	59	42	81	35	45	20	29	3	8	4	6	10	29	0
Sr	335	414	361	295	379	464	295	399	557	443	458	479	469	206	0
Th	3	4	3	3	3	4	0	0	0	0	1	0	0	5	0
V	225	197	166	233	186	204	158	168	168	231	264	243	192	254	0
Y	18	17	16	18	18	18	13	12	11	10	24	14	8	24	0
Zn	120	77	70	113	75	56	66	75	133	102	102	111	58	78	0
Zr	93	102	97	88	88	97	95	99	53	62	99	62	51	104	0
La	13	14	13	12	14	15			4	4	9	5	4	0	0
Ce	27	29	27	24	28	29			10	11	23	12	9	0	0
Pr	3	3	3	3	3	4			2	2	4	2	2	0	0
Nd	13	14	13	12	14	15			8	10	19	10	8	0	0
Sm	3	3	3	3	3	3			3	3	6	3	3	0	0
Eu	1	1	1	1	1	1			1	1	3	2	1	0	0
Gd	4	3	3	3	3	3			2	3	5	3	2	0	0
Tb	0	0	0	0	0	0			0	0	1	1	0	0	0
Dy	3	3	3	3	3	3			2	2	4	3	2	0	0
Ho	1	1	1	1	1	1			0	0	1	1	0	0	0
Er	2	2	2	2	2	2			1	1	2	1	1	0	0
Tm	0	0	0	0	0	0			0	0	0	0	0	0	0
FeO*	8.60	7.22	7.23	7.90	7.66	7.74			11.49	12.99	14.12	13.27	11.79	9.95	9.83
F/F+M	0.451	0.412	0.407	0.434	0.405	0.453			0.632	0.638	0.746	0.659	0.636	0.596	0.609
Rb/Sr	0.170	0.143	0.116	0.275	0.092	0.097			0.005	0.018	0.009	0.013	0.021	0.141	0.000
K/Rb	258	283	297	242	327	295			608	282	759	359	356	215	0
K/Ba	22.3	20.0	33.8	24.6	35.4	39.4			21.0	34.1	20.0	22.9	58.3	30.1	0.0
den	2.62	2.59	2.60	2.60	2.63	2.60			2.69	2.72	2.71	2.73	2.69	2.65	2.64

Table 5.1 (cont.)

Sample	LC-TML	LC-TML	LC-BIL
Group #	5.00	5.00	5.00
Qual	0	0	0
Key	6	6	6
Ref	0	0	0
SiO_2	50.36	58.49	53.54
TiO_2	0.79	1.19	2.08
Al_2O_3	16.87	18.91	19.58
FeO	8.69	6.32	9.70
MnO	0.15	0.12	0.37
MgO	12.12	3.80	4.03
CaO	8.06	5.97	6.12
Na_2O	2.21	3.24	2.90
K_2O	0.66	1.80	1.43
P_2O_5	0.10	0.16	0.26
Total	100.00	100.00	100.00
Ba	167	516	354
Cr	260	85	40
Nb	17	23	27
Ni	69	11	14
Rb	18	57	51
Sr	273	312	353
Th	2	3	5
V	146	126	230
Y	19	23	25
Zr	86	129	97
FeO*	8.69	6.32	9.70
F/F+M	0.421	0.629	0.714
Rb/Sr	0.066	0.183	0.144
K/Rb	307	262	233
K/Ba	33.0	29.0	33.5
den	2.67	2.52	2.61

Key

JD - Jeddore Dyke

SID - Sober Island Dyke

MD - Marshdale Intrusive

GD-P&B - Shelburne Dyke (Papezik & Barr, 1981)

GD-LAW - Shelburne Dyke (Lawrence, 1966)

LC-TML - Liscomb Complex, Ten Mile Lake Intrusive

LC-BIL - Liscomb Complex, Bog Island Lake Intrusive

Note

1. Majors recalculated to 100%, or a water-free basis

2. All Fe as FeO

Key for variation and discriminator diagrams

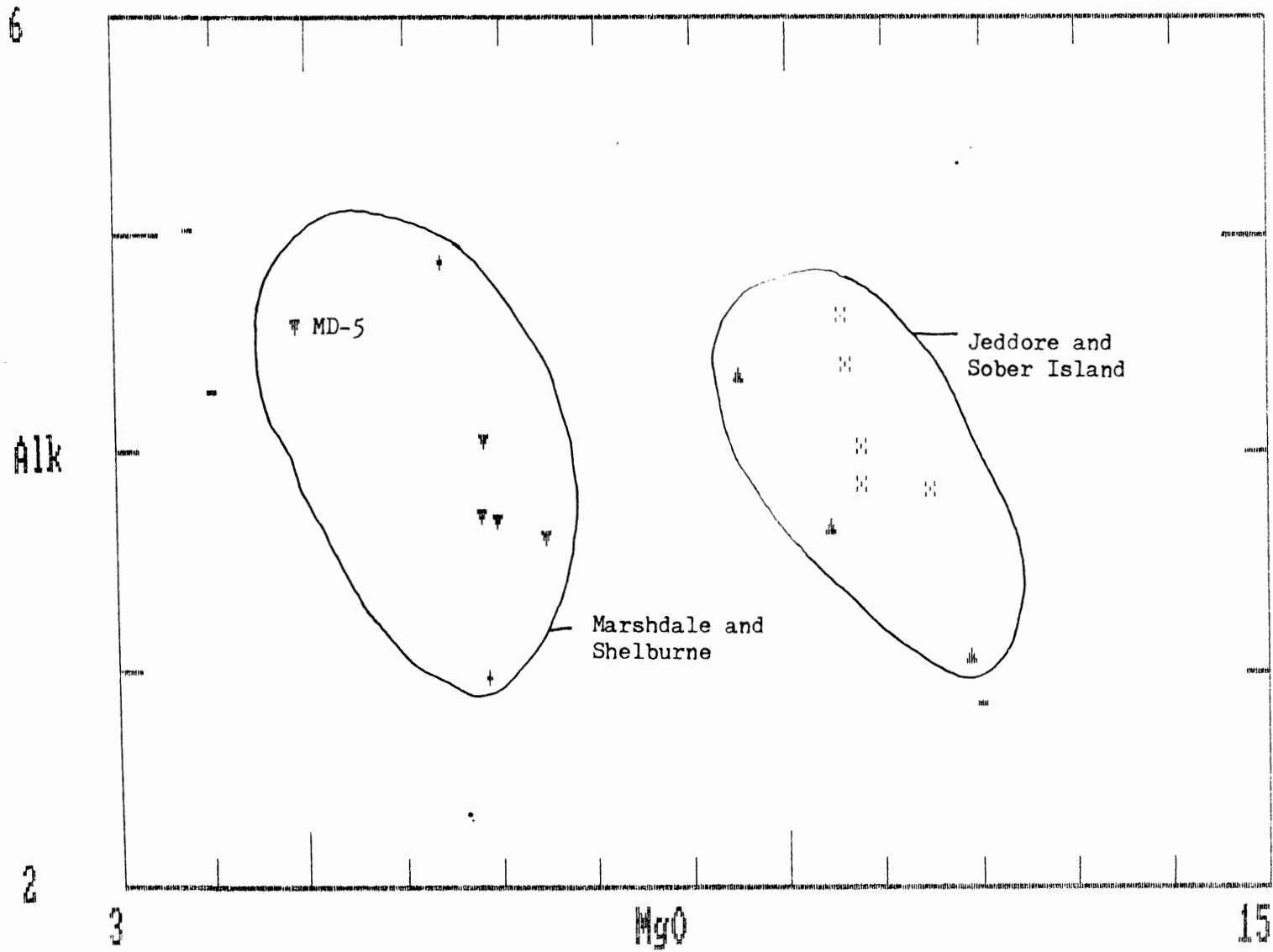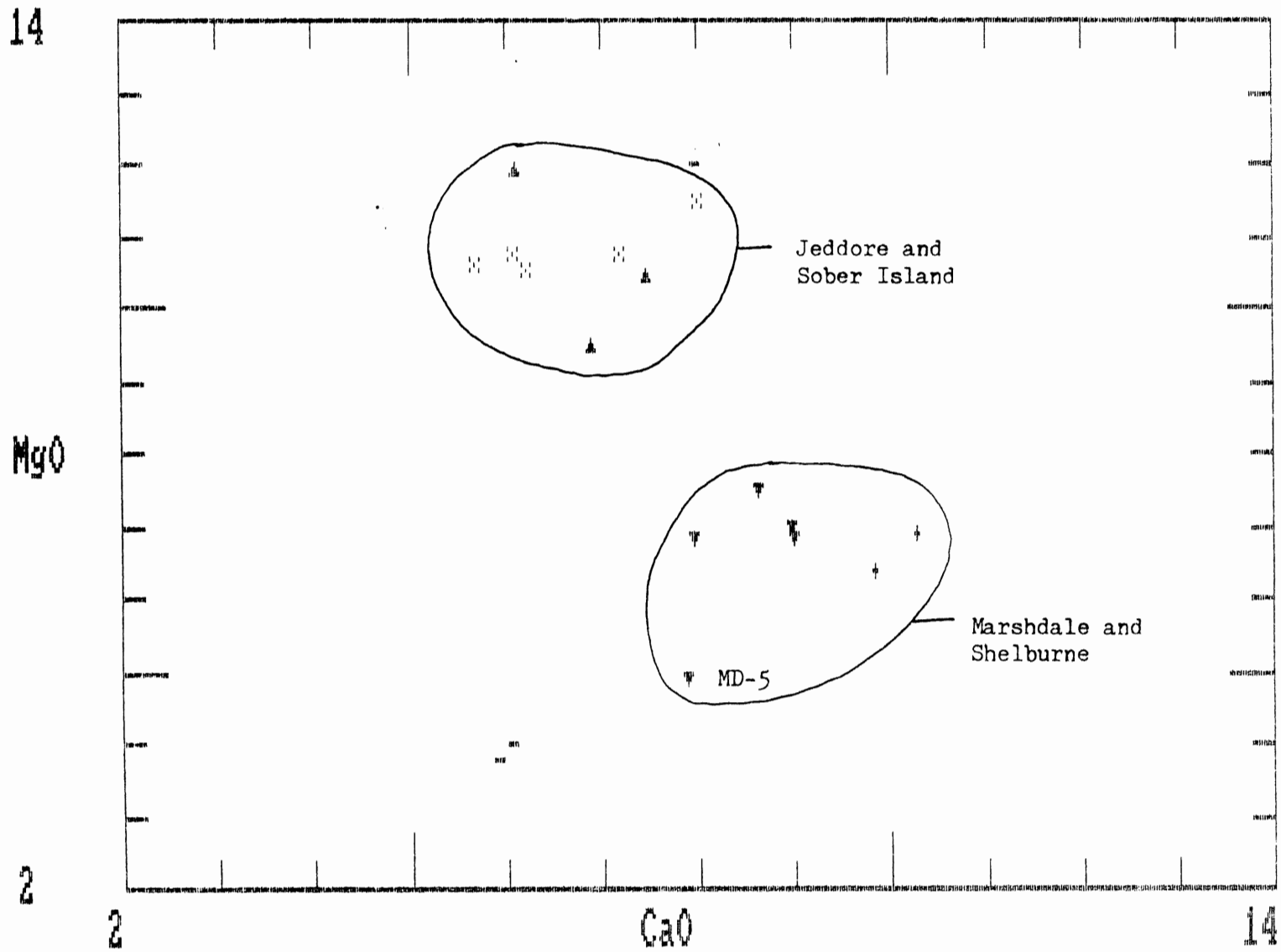|		
$\|_\|^\|$	-	Jeddore dyke
▲	-	Sober Island dyke
▼	-	Marshdale intrusive
▬	-	Liscomb Complex
+	-	Shelburne dyke
◯	-	chemical group

Figure 5.1   Major vs. Major
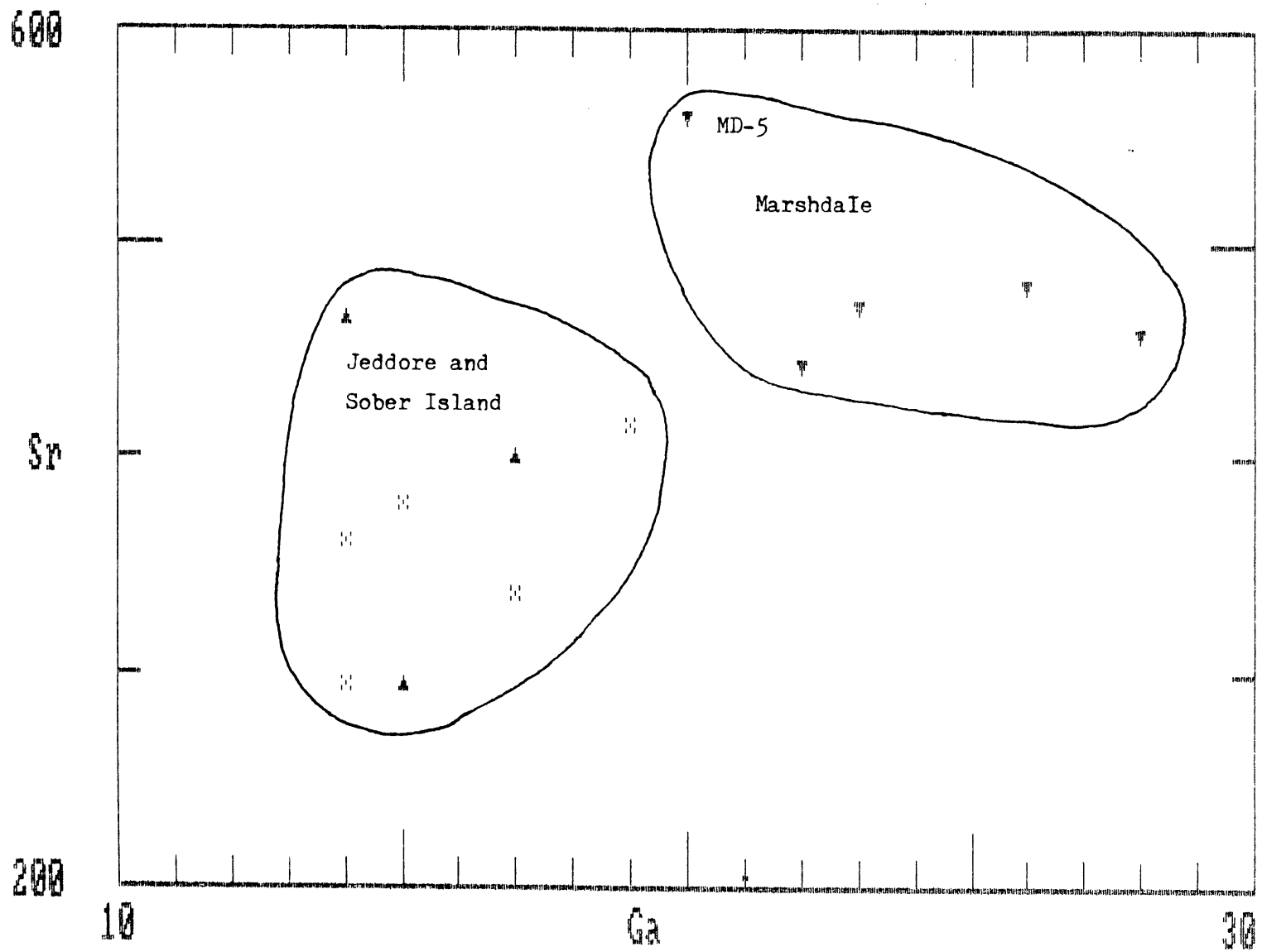
Figure 5.2   Major vs. Major
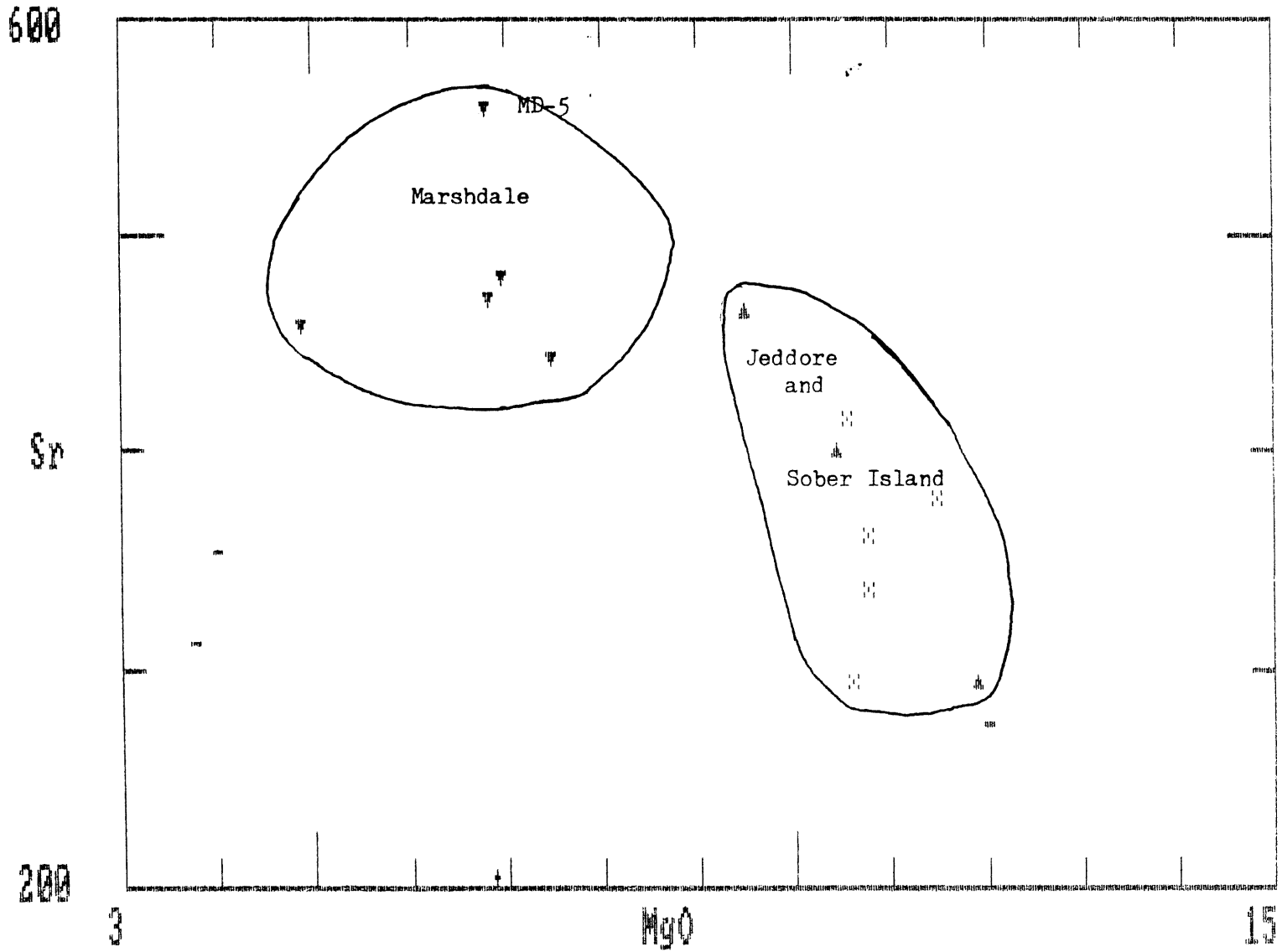
Figure 5.3 Trace vs. Trace

Figure 5.4 Trace vs. Major

intrusive is chemically very different. Chemically, it is more similar to the Shelburne dyke than the other two. A secondary observation is that sample MD-5 is unlike the other four Marshdale samples. This difference was also noted in the petrograghy of this body and will be discussed later.

5.1.2 Ternary Discriminator Diagrams

The tectonic environments of the various intrusions were ascertained using a set of ternary diagrams selected for the information they give. Care is required when drawing conclusions from these diagrams because the diagrams are based on basalts and none of the intrusions in this thesis is a basalt. They do, however, have basaltic compositions.

Figure 5.5 shows that the Marshdale intrusive is tholeiitic whereas the Jeddore and Sober Island dykes are calc-alkaline. Figures 5.6 and 5.7 also show that the two eastern shore dykes are calc-alkaline. Unfortunately, the Marshdale intrusive does not plot within the fields of these latter diagrams on account of the high percentage of titanium in this intrusion.

5.1.3 Rare Earth Element (REE) Diagrams

The five Jeddore dyke REE patterns were combined with the one Sober Island dyke REE pattern in Figure 5.8. The LREE enriched patterns of both dykes are nearly identical.
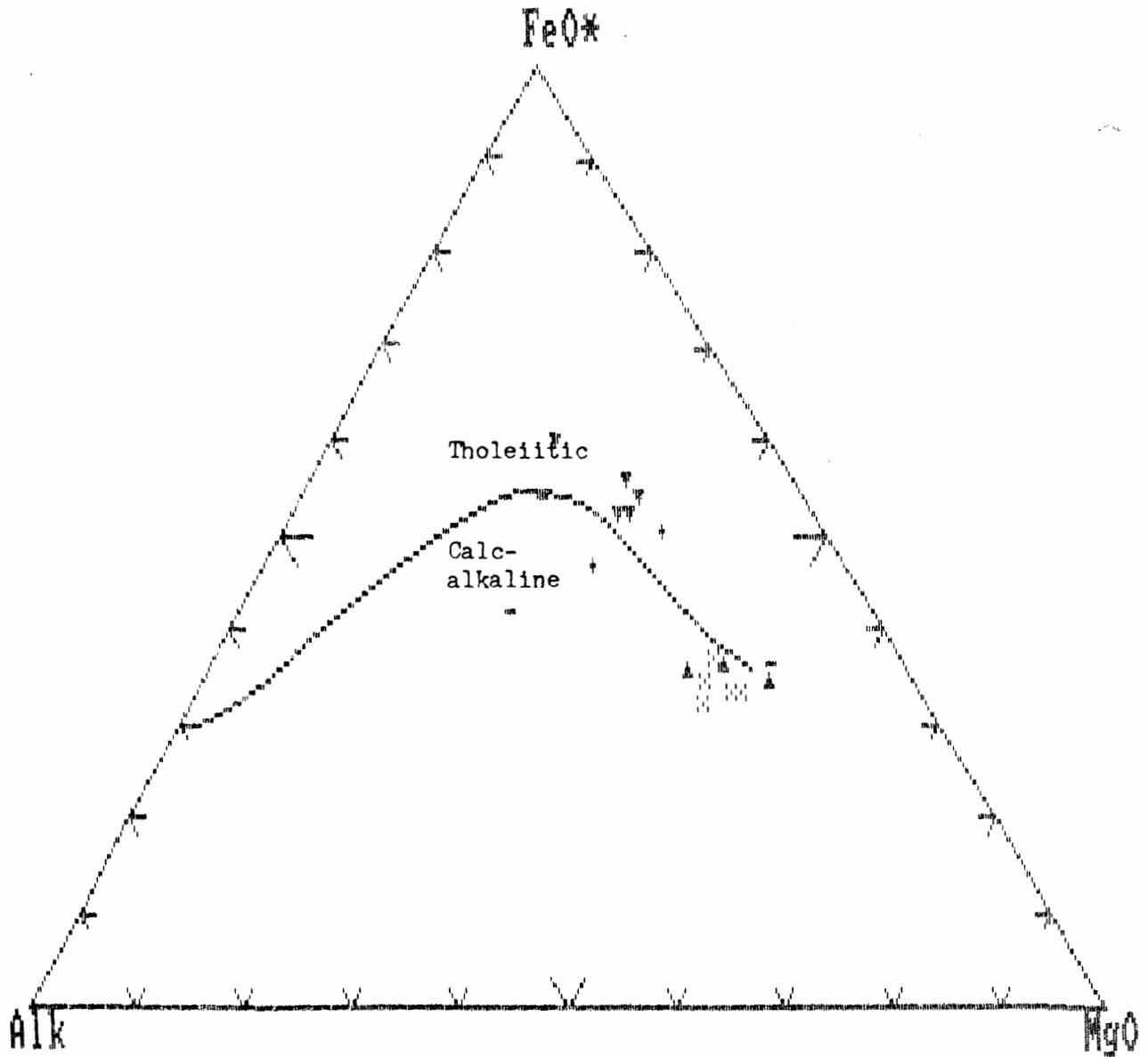
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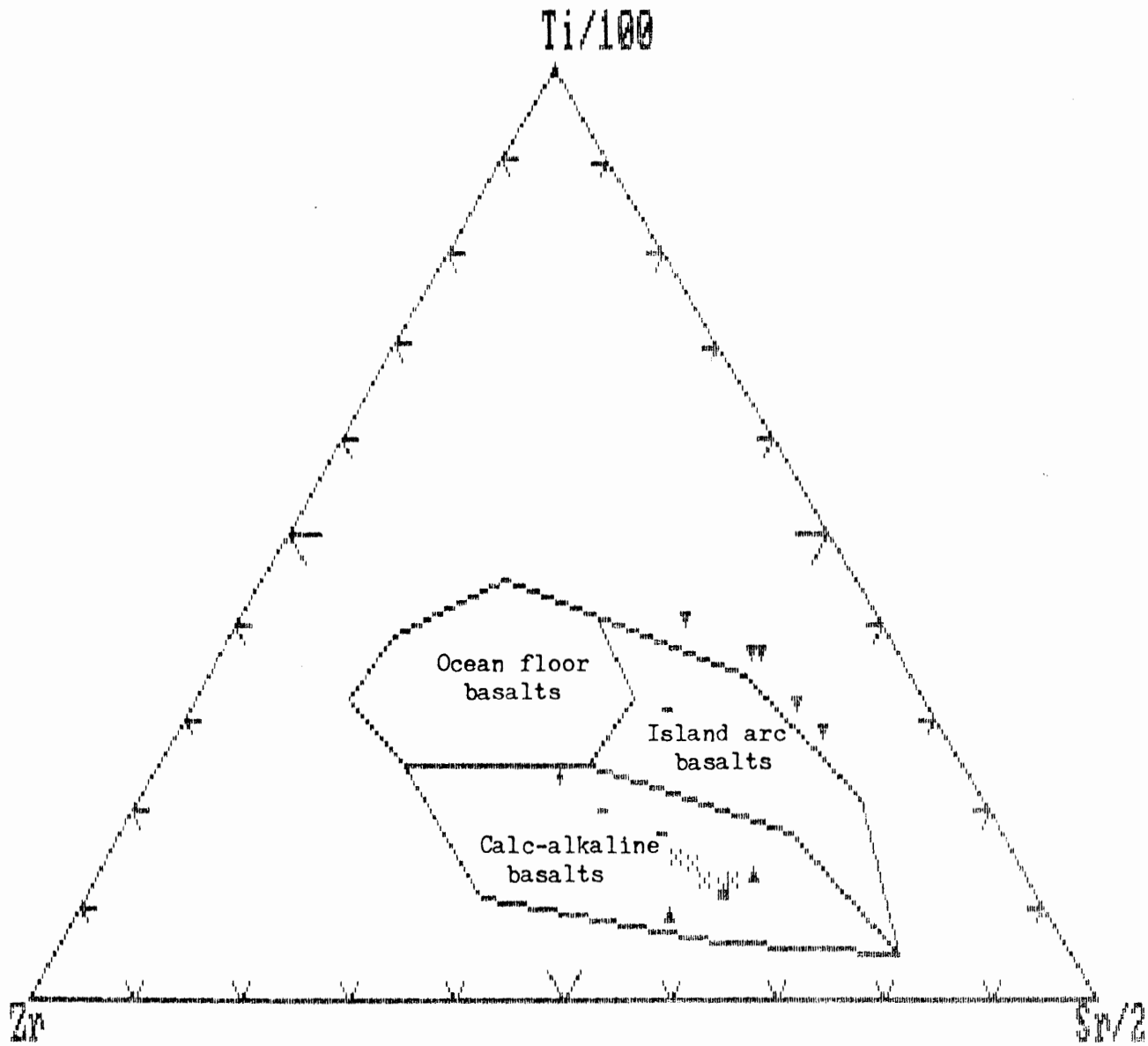Figure 5.5 after (Irvine & Barager, 1971)
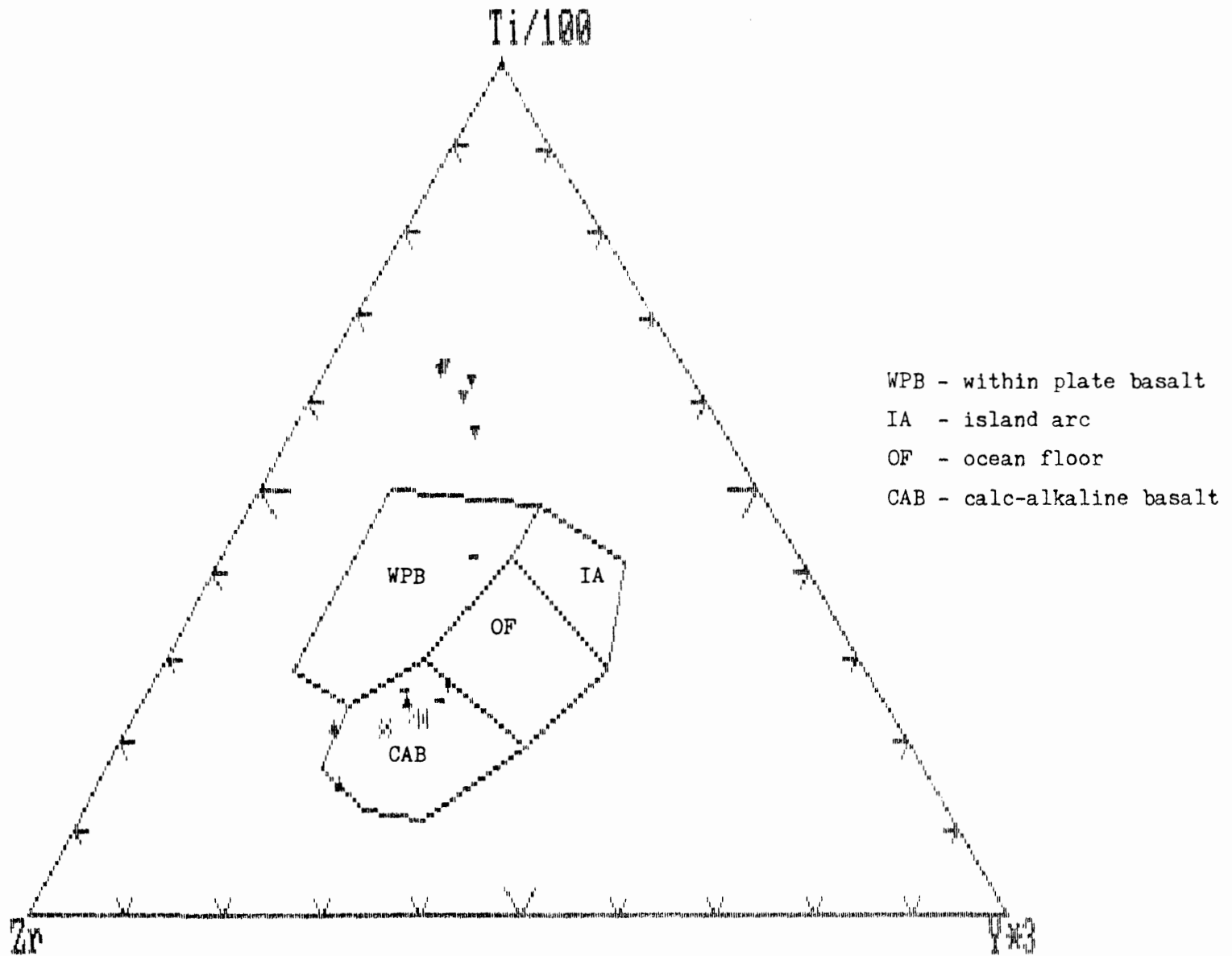
Figure 5.6 after (Pearce & Cann, 1975)

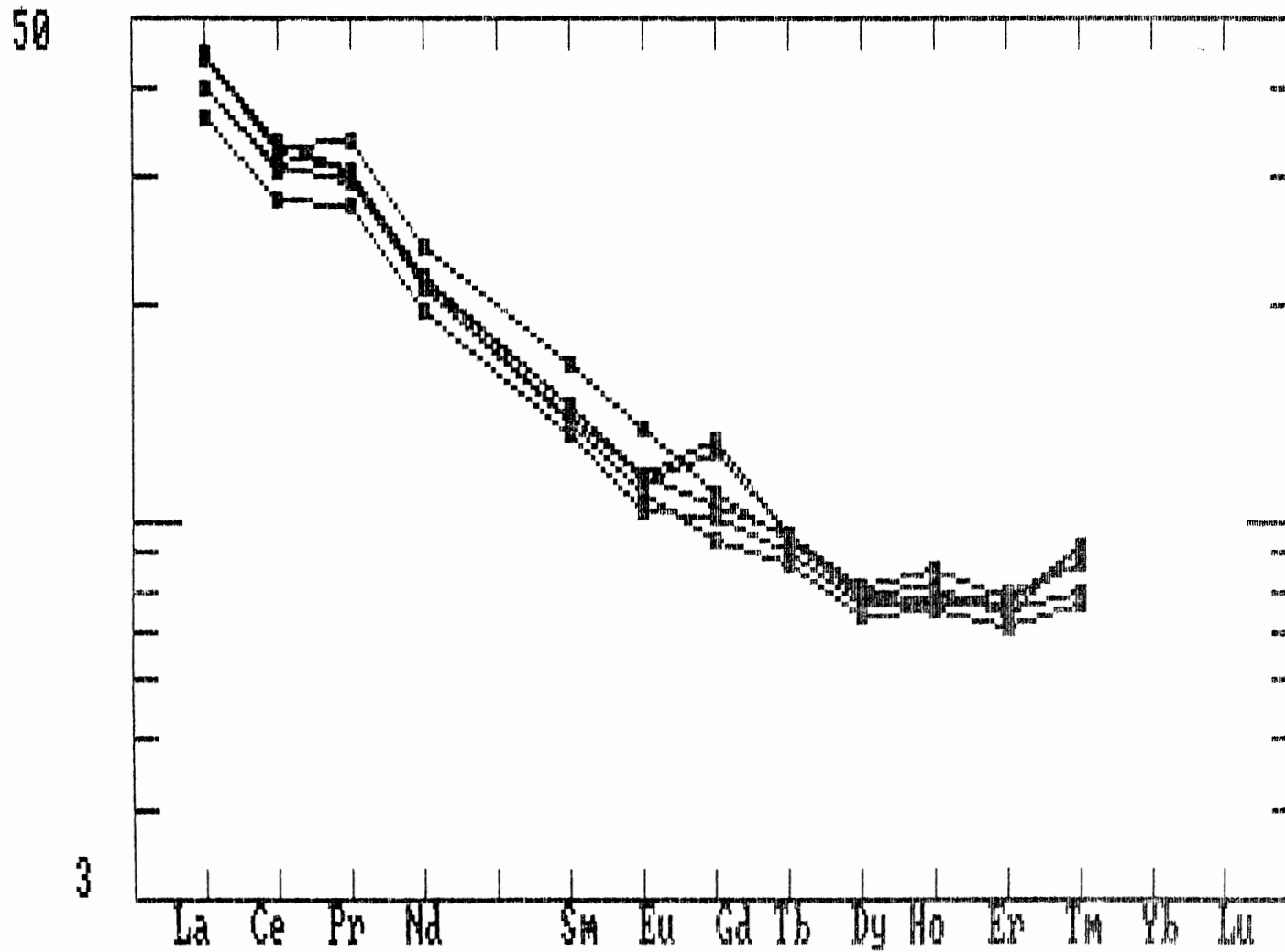Figure 5.7 after (Pearce & Cann, 1975)

Figure 5.8. REE patterns for the Jeddore and
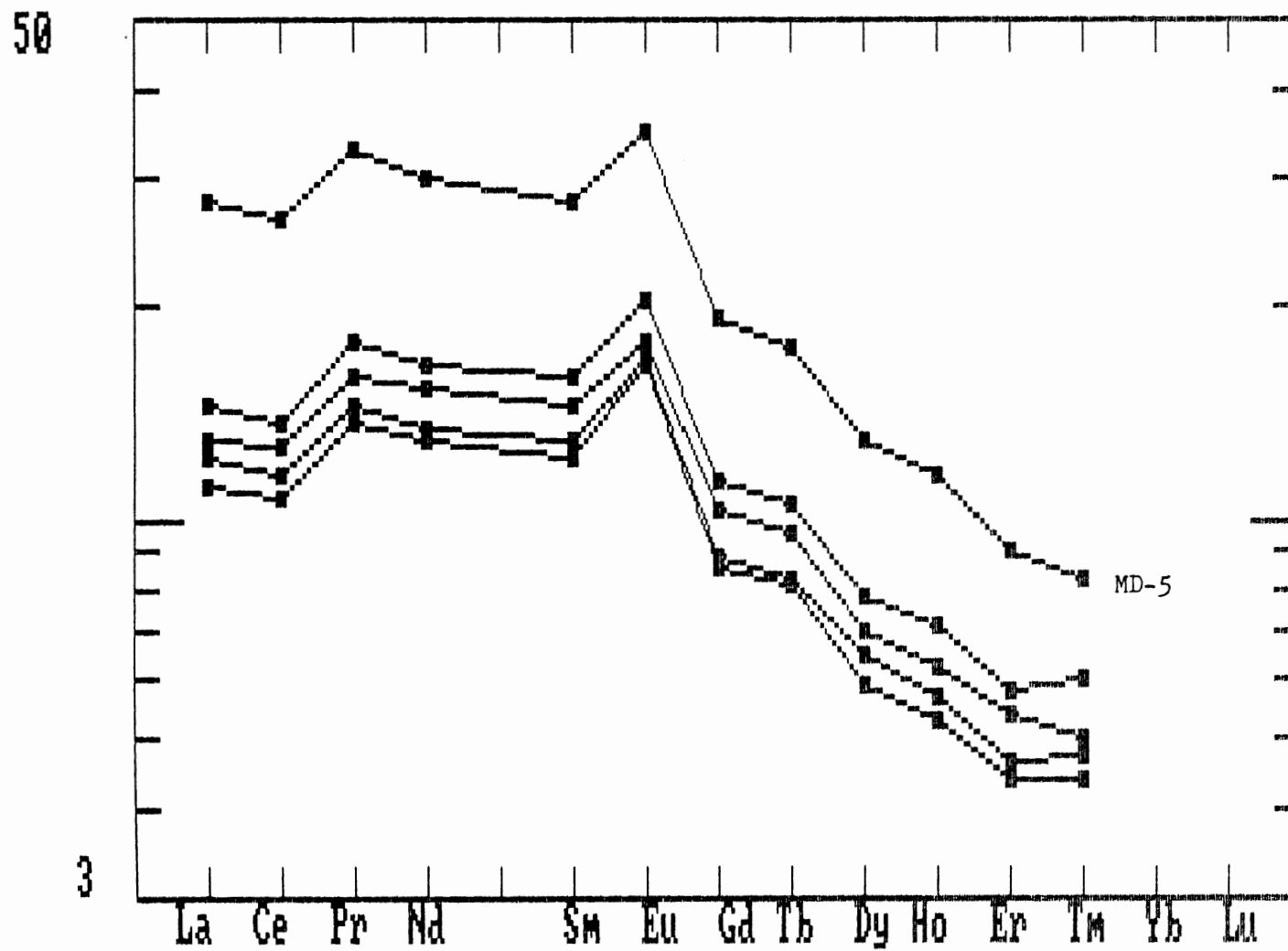Sober Island dykes.

Figure 5.9.   REE pattern for the Marshdale
intrusive.

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The REE patterns for the Marshdale intrusive (Fig. 5.9) show both enrichment in the middle REE's and marked positive Eu anomalies, both considerably different from the other two bodies The large amount of plagioclase (in which Eu^{+2} is compatible) in the Marshdale intrusive can explain the positive Eu anomaly. Another feature of note is the elevated pattern of sample MD-5, again setting this sample apart from the rest of the Marshdale body. It suggests that late stage magmas rich in REE's and other incompatible elements, such as Ba, solidified at the spot where sample MD-5 was collected, possibly representing the center of the intrusion.

5.2 Reclassification of the Jeddore and Sober Island Dykes

Based on mineralogy and mineral compositions, the term diorite was used to describe the Jeddore and Sober Island dykes. Although this term is applicable, a more precise chemical classification is possible. A.K. Chatterjee (pers. com., 1987), working on a similar dyke, suggested that the Jeddore and Sober Island dykes might also be calc-alkaline lamprophyres. A geochemical and mineralogical screen created by Rock (1984) provides the necessary information to test this idea. The screen (Fig. 5.10) is based on over 1000 analyses of reported lamprophyres. In addition to the screen, a further set of criteria for the identification of calc-alkaline lamprophyres is also given by Rock (1984, 1977). These criteria are as follows:

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<u>Calc-alkaline Lamprophre Screen</u>

Mineralogy

			<u>JD</u>	<u>SID</u>
1.	amphibole + bt.	> 20%	40-50%	40-50%
2.	qtz. + analcime	< 10%	5%	5%
3.	colour index	35-67	~ 60	~ 60
4.	no olivine, opx, $\pm$ muscovite, titanaugite (others)		✓	✓

Mineral Chemistry
Amphiboles

1.	wt.% MgO	> 10	14.2-15.3	14.5-14.8
2.	wt.% Na_2O	> 1	1.85-2.4	2.2-2.3
3.	wt.% K_2O	0.3-2	0.47-0.68	0.5-0.7
4.	wt.% TiO_2	> 1	1.5-2.86	2.4-2.7

Bulk Rock Chemistry

			typically		
1.	SiO_2	42-62%	46-57%	52%	52%
2.	TiO_2	0.3-3%	0.5-2%	0.67%	0.3%
3.	Al_2O_3	9-20%	11-18%	14%	15%
4.	*FeO	4-11%	5-10%	8%	9%
5.	MgO	1.5-13%	3.5-9.5%	10%	9%
6.	MnO	< 0.4%	< 0.2%	0.18%	0.13%
7.	CaO	1.5-12%	4-9%	6%	6.5%
8.	Na_2O	0.5-5%	1.5-4%	2%	1.5%
9.	K_2O	0.5-10%	1-6%	2%	0.13%
10.	P_2O_5	< 2%	< 1.1%	0.11%	0.11%

*FeO - all Fe as FeO

JD - Jeddore Dyke

SID - Sober Island Dyke

Figure 5.10 from Rock (1984)

-- occur as dykes or sills

-- explosive emplacement not uncommon

-- invariably porphyritic

-- hydrous mineralogy (e.g. biotite/amphibole) essential

-- absence of felsic phenocrysts and groundmass olivine

-- typically high degree of alteration, especially in groundmass

-- frequently contain xenoliths

-- chemically intermediate to ultramafic

-- often accompany aplites, pegmatites, or carbonatites

(Rock, 1984, 1977)

The Jeddore and Sober Island dykes meet most of these criteria and both pass the calc-alkaline screen of Rock (1984). This suggests that, although the term diorite is acceptable, calc-alkaline lamprophyre can be used as a more precise chemical name

5.3   Conclusions

1. Although diorite is an appropriate name for the Jeddore and Sober Island dykes, the majors, traces, mineral chemistry and texture, all indicate that calc-alkaline lamprophyre is a more precise chemical name.

2. The Jeddore and Sober Island dykes form one chemical group (variation diagrams), are calc-alkaline (discriminators and screen), and have essentially the same REE patterns. This evidence suggests both dykes formed from the same magma.

3. The Marshdale intrusive forms a distint chemical group, and has a REE pattern unlike those from the other intrusions.

4. Chemically, the Shelburne dyke is most similar to the Marshdale intrusive, although this similarity is insufficient to prove a common origin for these two bodies.

5. The Liscomb Complex is chemically too variable to make any meaningful conclusions about genetic relationships or classifications.

Chapter 6:   Geochronology

6.1   Introduction

The hornblendes of the Jeddore and Sober Island dykes
contain   sufficient   potassium   to   use $^{40}Ar-^{39}Ar$ dating.
Unfortunately this technique can not be applied to the Marshdale
intrusive because the potassium content of that body is
exceptionally low.   A brief summary of the procedure for
separating and dating the hornblende is given in Appendix III. A
complete explanation of the $^{40}Ar-^{39}Ar$ dating principles and
techniques is found in Dalyrymple and Lanphere (1969).

6.2   Jeddore Dyke

Figure 6.1 shows that 45% of the gas is released in two
heating steps, giving an age of 371-375 Ma. A gap, caused by the
release of a small amount of argon gas with a very high error,
occurs at the left edge of the graph. The most important steps
are those over which the most gas is released, so this gap is not
problematic.

6.3   Sober Island Dyke

A very convincing plateau, over which 35% of the argon gas
is released, occurs at 371$\pm$Ma. (Fig. 6.2).   This plateau
represents two heating steps.

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Figure 6.1   <u>Jeddore Dyke</u>

380

age
(million years)

280

0

cumulative % ^{39}Ar released

100

69

Figure 6.2   <u>Sober Island Dyke</u>

380

age

(million
years)

70

280

0   100

cumulative % ^{39}Ar released
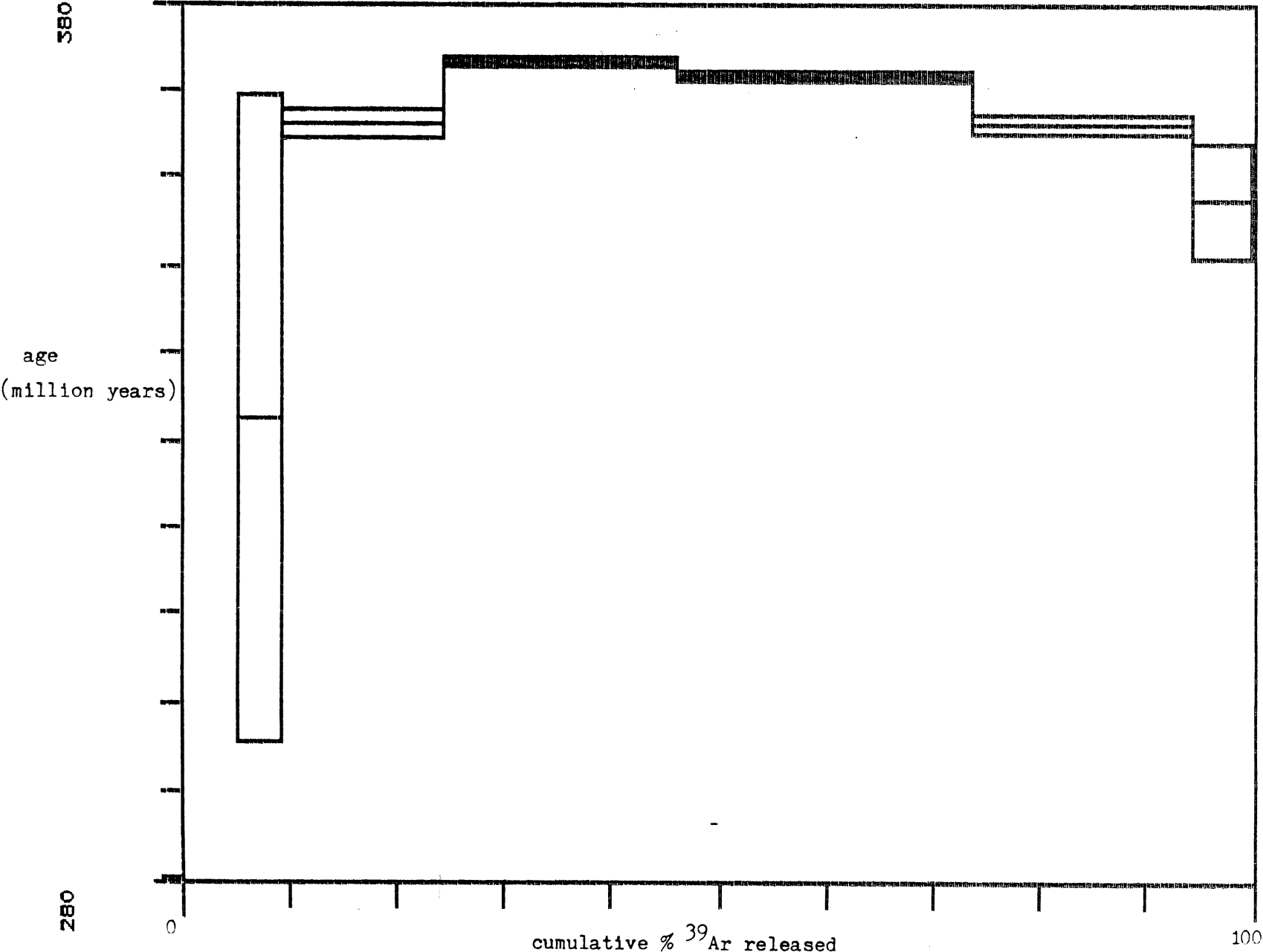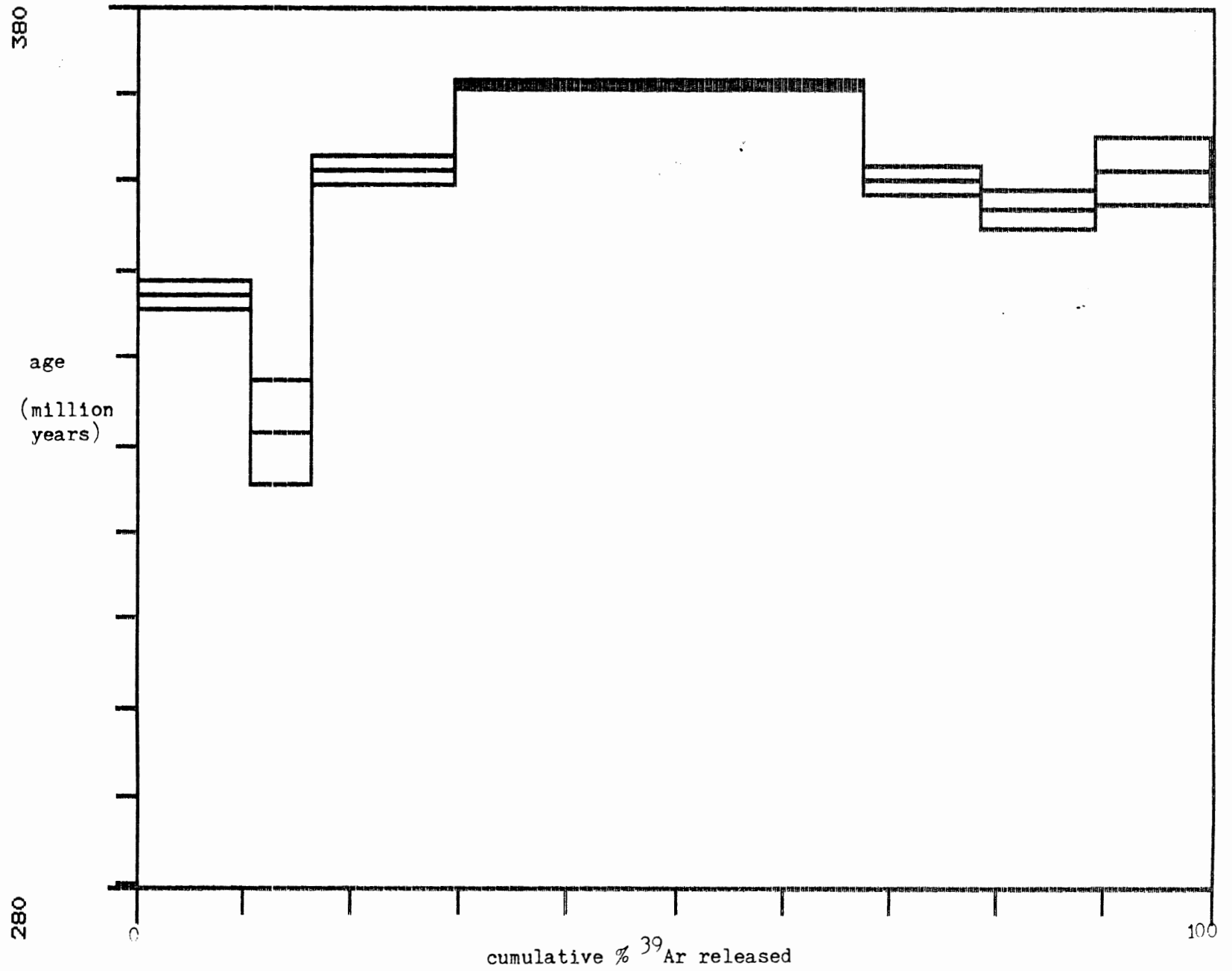
6.4   Comparisons

The age estimates for both the Jeddore dyke, and the Sober Island dyke are essentially identical indicating that both have similar crystallization histories and that both were emplaced during the same igneous event.   The age of 370 $\pm$ 5 Ma. obtained by the $^{39}Ar-^{40}Ar$ technique is not necessarily the age of emplacement, but rather the age when the argon gas was trapped by the solidification of the hornblende crystal.   The age can, however, be considered a reasonable estimate   raising some interesting questions which are discussed in the next chapter.

Although the Marshdale intrusive and Shelburne dyke were not dated in this study, some useful comparisons can still be made. Previous work by Lawrence (1966), and Papezik & Barr (1981), show that the Shelburne dyke is Triassic meaning that there is no relationship between the two eastern shore dykes and the Shelburne dyke.   The   Marshdale   body   intrudes   rocks of Carboniferous age indicating that it is post-Carboniferous.   As such, it is significantly younger than the Jeddore and Sober Island dykes, and could be the same age as the Shelburne dyke.

6.5   Conclusions

The following conclusions can be made from the evidence presented in this chapter:

1. The Jeddore and Sober Island dykes formed approximately 370 million years ago, meaning that they are not members of the ENA swarm as was suggested in the first Chapter. This age coincides with the age of several other major intrusions in Nova Scotia such as the South Mountain batholith and Musquodoboit batholith.

2. The Shelburne dyke is Triassic eliminating any possibility of a simple relationship with the Jeddore and Sober Island dykes.

3. The Marshdale intrusive is post-Carboniferous in age and is therefore significantly younger than the Jeddore and Sober Island dykes. It may be the same age as the Shelburne dyke, however.

Chapter 7:   Discussion and Implications of Results

7.1   Introduction

The age and composition of the Jeddore and Sober Island dykes raise a number of interesting questions.   The ages of the two dykes are essentially identical to the age determined for major granitic intrusions in Nova Scotia, such as the South Mountain batholith and the closer Musquodoboit batholith, meaning that granitic and lamprophyric magmas were intruded contemporaneously.   This relationship is not unique to Nova Scotia.   Rock (1984) points out that calc-alkaline lamprophyres associated with granitic plutons are almost always contemporaneous.   How do two magmas, the granitic and lamprophyric, with totally different compositions become intruded at the same time?   Did the two magmas originate from the same magma chamber?   Is one magma simply a fractionation product of the other?   What caused this period of igneous activity?   Some of these questions will be discussed in the next Section followed by the presentation of a petrogenetic model.

7.2   Discussion

Questions two and three are closely related because to say that both magmas originated from the same magma chamber is to say that one magma is a fractionation product of the other, given that both magmas intruded contemporaneously.   Although this

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mechanism for lamprophyric genesis has been proposed in the past (e.g. Vogel & Wilbrand, 1978), it is not widely accepted (Rock, 1984). One feature opposing the single magma chamber and fractionation hypothesis is the vast difference in compositions of the two magmas and the absence of intermediate products.

A second possibility for the generation of two distinct magmas is to have two separate source areas. Ascension and emplacement of the resulting intrusions could still represent the same igneous event. Two lines of evidence support the two source theory. Rock (1984) presents convincing evidence to support the hypothesis that calc-alkaline lamprophyres represent crustal modification of K-rich, mantle derived magmas, and that those associated with granites have undergone the greatest modification because they pass through magmatically active crust. The granite batholiths of Nova Scotia are peraluminous suggesting a crustal source (Clarke & Muecke, 1985). If the lamprophyres are mantle-derived and the granites are crustal-derived then the single chamber, fractionation model cannot be correct.

7.3   Petrogenetic Model

The devolopment of a viable model is necessary to answer the final question and to explain all the observations.

The granite batholiths have a crustal origin (Clarke & Muecke, 1985), meaning that the lower crust must have become

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heated.   Two possible mechanisms to provide the necessary heat
are:

a) a subduction zone

b) crustal thickening

Because the major granite batholiths are peraluminous, S-type
granites, and because there is an absence of andesitic rocks, the
subduction zone model can be ruled out.

When the dykes and batholiths were emplaced, Nova Scotia had
already collided with Africa judging from the deformation of the
Acadian Orogeny.   This collision caused the compression of
sediments which in turn caused a thickening of the crust. The
lower crust began to melt and then ascended to the surface in the
form of granitic batholiths.   This mechanism is known as a
Hercynotype Orogen (Pitcher, 1979). It explains the presence of
the granites, but does not address the problem of the associated
lamprophyres.   Referring back to Rock's idea that granite-
associated lamprophyres represent crustal-modified, mantle-
derived magmas, the lamprophyres clearly have a different source.
The heat source which melted the lower crust to form the granite
batholiths must have also heated the mantle source region for the
lamprophyres.   This heat source may have been a hot spot, or may
have been caused by underplating.   Kinetically it was probably
easier for the lamprophyric magma to ascend through the cold,
solid, country rock than through the semi-solid granitic magma
chamber, thereby explaining the abundance of lamprophyric dykes
away from the batholiths.

This model can explain fairly well the relationship between the calc-alkaline lamprophyres (Jeddore and Sober Island dykes) and the temporally associated granitic batholiths (South Mountain and Musquodoboit batholiths).

Chapter 8:   Summary of Conclusions and suggestions for further
              work

8.1   Conclusions

     Below is a summary of all the conclusions made in the
preceding chapters.

1.   Based on the lack of clear field relations, the cumulate
     texture of the rock, and the circular magnetic anomaly, the
     Marshdale intrusive can be considered a plug.

2.   Although the mineralogical term diorite is appropriate for
     the Jeddore and Sober Island dykes, Calc-alkaline lamprophyre
     is a more precise chemical name. The proper name for the
     Marshdale body is a gabbroic plug.

3.   The amphiboles of the Jeddore and Sober Island dykes are
     primary hornblende with the exception of one Jeddore sample.
     The amphibole of the Marshdale intrusive on the other hand is
     secondary actinolite.

4.   The size, orientation and chemistry of the Jeddore and Sober
     Island dykes are sufficiently similar to suggest that they
     originated from the same magma chamber and are genetically
     related.

5.   The chemistry and mineralogy of the Marshdale intrusive are totally unlike the eastern shore dykes, but they do show similarities with the Shelburne dyke.

6.   Sample MD-5 is unlike the other Marshdale samples both chemically and mineralogically. This may be the result of a late stage magma, rich in incompatible elements, solidifying at the spot where sample MD-5 was collected.

7.   The mineralogy of the Liscomb Complex is significantly different (e.g. presence of garnet xenoliths and biotite) to suggest that it was generated from a separate magma from the other bodies, although it may have intruded during the same igneous event.

8.   The presence of hornblende and intermediate plagioclase in the Jeddore and Sober Island dykes suggests a crystallization temperature of 825°C-950°C. This is 100°C less than that of the Marshdale intrusive, which contains higher temperature minerals such as olivine, pyroxene and calcic plagioclase.

9.   A temperature of 725°C-850°C, representing the temperature at which ilmenite exsolved from magnetite, was obtained using the geothermometer of Buddington and Lindsley (1964).

10. $^{40}Ar-^{39}Ar$ dating shows the Jeddore and Sober Island dykes are the same age of 370 +/- 5 million years. The Marshdale

intrusive intrudes rocks of Carboniferous age, so must
therefore be younger than the two eastern shore dykes.

11.   The   ages determined   for the   Jeddore and Sober Island dykes
       (370 Ma.) clearly exclude them from being part of the ENA
       dyke swarm (200 Ma.).

8.2   Suggestions for further work

The work in this thesis could be followed up in a number of
different ways.   The chemical data could be used to formulate
fractionation models,   isotope work could result in better
constraints on the source for each body, and tracing the two
dykes over a larger area could show a closer association to the
granitic plutons in the area.

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Amphibole Recalculation (13eNKCa)

	wt.%	# cations based on 23 oxygens	normalized to 13 minus Na, K, Ca	anions of O	
SiO_2	42.44	6.27	6.15	12.30	
TiO_2	2.37	.262	.256	.514	
Al_2O_3	12.02	2.09	2.05	3.07	
Cr_2O_3	0.21	.023	.023	.034	
*FeO	10.76	1.33	1.30 (.925) (.374)	1.30	$Fe^{3+} = 2(23-22.537)$ $= .925$
MnO	0.22	.025	.025	.025	$Fe^{2+} = 1.30-.925$
MgO	14.84	3.26	3.20	3.20	$= .374$
CaO	11.10	1.75	1.72	1.72	
Na_2O	2.27	.649	.636	.636	
K_2O	0.62	.115	.113	.113	
	96.83	15.77	13	22.537	

Si 6.15
Al(IV) 1.85
8.00

Al(VI) .200
Ti .256
Cr .023
Fe^{3+} .925
Mg 3.20
Fe^{2+} .374
Mn .022
5.00

Fe^{2+} ---
Mn .003
Ca 1.72
Na .277
2.00

Na .359
K .113
.472

*FeO – all Fe as FeO

Recalculation of Ilmenite

	original wt.%	cations based on 1 oxygen	cations based on 24 oxygens	normalized to 16 cations	anions of O	
TiO_2	45.97	.3063	7.35	7.07	14.14	$Fe^{3+}=2(24-23.073)$
Al_2O_3	0.08	.0008	.019	.018	.027	$Fe^{3+}=2(.927)$
*FeO	50.10	.3713	8.91	8.57	8.57	$Fe^{3+}=1.85$
MnO	0.55	.0041	.098	.094	.094	$Fe^{2+}=8.57-1.85$
MgO	$\underline{0.80}$	$.0105$	$\underline{.252}$	$\underline{.242}$	$\underline{.242}$	$Fe^{2+}=6.72$
	97.49		16.629	16	23.073	

	# cations	# anions			col.8	recal. wt.%
Ti	7.07	14.14	TiO_2	$=(7.07 \times 47.90)+(14.14 \times 16) =$	564.9	46.51
Al	.018	.027	Al_2O_3	$=(.018 \times 26.98)+(.027 \times 16) =$	.92	0.08
Fe^{3+}	1.85	2.78	Fe_2O_3	$=(1.85 \times 55.85)+(2.78 \times 16) =$	147.7	12.18
Fe^{2+}	6.72	6.72	FeO	$=(6.72 \times 55.85)+(6.72 \times 16) =$	482.8	39.81
Mn	.094	.094	MnO	$=(.094 \times 54.94)+(.094 \times 16) =$	6.66	0.55
Mg	$\underline{.242}$	$\underline{.242}$	MgO	$=(.242 \times 24.31)+(.242 \times 16) =$	$\underline{9.75}$	$\underline{0.80}$
	16	24			1212.73	100%

Steps : same as for magnetite

*FeO - all Fe as FeO

Amphibole Recalculation (all FeO assumption)

	wt.%	cations based on 23 oxygens				
SiO_2	52.27	7.62	Si	7.62		
TiO_2	0.28	.030	Al(IV)	$\underline{0.38}$	Fe^{2+}	.277
Al_2O_3	3.32	.568		8.00	Mn	.032
Cr_2O_3	0.09	.009			Ca	1.69
*FeO	15.98	1.95	Al(VI)	.188	Na	$\underline{.001}$
MnO	0.27	.032	Ti	.030		2.00
MgO	14.30	3.10	Cr	.009		
CaO	10.83	1.69	Fe^{3+}	---	Na	.107
Na_2O	0.39	.108	Mg	3.10	K	$\underline{.016}$
K_2O	$\underline{0.09}$	$\underline{.016}$	Fe^{2+}	$\underline{1.673}$		.123
	97.81	15.12		5.00		

*FeO - all Fe as FeO

Recalculation of Magnetite

original wt.%		cations based on 1 oxygen		cations based on 32 oxygens	normalized to 24 cations	anions of O	
SiO_2	0.05	Si	.0004	.013	.011	.022	
TiO_2	12.75	Ti	.1020	3.26	2.82	5.64	
Al_2O_3	3.97	Al	.0498	1.59	1.37	2.06	$2(32-27.64)=Fe^{3+}$
Cr_2O_3	1.02	Cr	.0085	.272	.235	.352	$2(4.36)=Fe^{3+}$
*FeO	75.04	Fe	.6677	21.37	18.47	18.47	$Fe^{3+}=3.72$
MnO	0.28	Mn	.0024	.077	.067	.067	$Fe^{2+}=9.75$
MgO	2.34	Mg	.0371	1.19	1.03	1.03	
	95.44			27.77	24	27.64	

	# cations	# anions		col. 8	recal. wt.%
Si	.011	.022	$SiO_2 = (.011 \times 28.09)+(.022 \times 16) =$	.661	.04
Ti	2.82	5.64	$TiO_2 = (2.82 \times 47.90)+(5.64 \times 16) =$	225.34	12.83
Al	1.37	2.06	$Al_2O_3 = (1.37 \times 26.98)+(2.06 \times 16) =$	69.92	3.98
Cr	.235	.352	$Cr_2O_3 = (.235 \times 51.99)+(.352 \times 16) =$	17.35	1.02
Fe^{3+}	3.72	13.08	$Fe_2O_3 = (3.72 \times 55.85)+(13.08 \times 16)=$	696.3	39.63
Fe^{2+}	9.75	9.75	$FeO = (9.75 \times 55.85)+(9.75 \times 16) =$	700.5	39.87
Mn	.067	.067	$MnO = (.067 \times 54.94)+(.067 \times 16) =$	4.75	.27
Mg	1.03	1.03	$MgO = (1.03 \times 24.31)+(1.03 \times 16) =$	41.51	2.36
	24	32		1756.8	100%

Steps

1. column 2 multiplied by 32

2. column 3 multiplied by 24/27.77

3. column 4 multiplied by 2, 1.5 or 1 depending on charge of cation

4. conversion of enough Fe to Fe^{3+} to make column 5 total 32

5. # of cations and anions multiplied by atomic weights to get column 8

6. each value of column 8 divided by 1756.8 to obtain percentages

*FeO - total Fe as FeO

Appendix III

Analytical Methods

$^{40}Ar-^{39}Ar$ dating:

Hornblende separated from one sample of the Jeddore dyke and one sample of the Sober Island dyke were used for Ar-Ar age dating. Separation techniques involved magnetic and heavy liquid separation, as well as hand picking.

Samples weighing 0.2g. were sent to McMaster University to be irradiated with fast neutrons. This process converts the potassium isotope ^{39}K to ^{39}Ar.

The samples were returned to Dalhousie for the next step in the process. The samples are carefully heated incrementally, in a high vacuum extraction system; one hour for each step. Argon gas trapped in the lattice of the hornblende is thus released along a series of tubes where it becomes purified. The purified argon gas then enters a mass spectrometer where each of its isotopes is measured (Gleadow & Harrison, 1987).

A computer then calculates the ratios of the various isotopes to make necessary corrections for atmospheric argon, argon produced from the irradiation of Ca, and from ^{40}Ar not produced from the forced decay of potassium. The percentage of

argon outgassed and an age is are computed for each heating step

using the equation: $t = \frac{1}{\lambda} \ln \left\{ 1 + J \left(\frac{^{40}Ar}{^{39}Ar} \right)_u \right\}$

<div align="right">(P.Reynolds, pers. com., 1988)</div>

These are plotted on a graph such as Figures 6.1 & 6.2 and an

overall age is then estimated.

X—Ray Fluoresence

X—ray fluoresence was used to determine the bulk rock

analyses found in this thesis. The procedure which involves the

bombardment of a powdered sample with X—rays, was done at Saint

Mary's University in Halifax. This technique is usually accurate

to 5ppb and is repeatable to about 1 or 2 ppm.