THE WHITE ROCK FORMATION METAVOLCANICS AT CAPE ST. MARY, NOVA SCOTIA: PETROGRAPHY, GEOCHEMISTRY, AND GEOLOGIC AFFINITIES

BY

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ABSTRACT

A 156 meter thick section of the Silurian White Rock Formation occurs at Cape St. Mary, southern Nova Scotia in the core of a southwest plunging syncline. It includes four metabasite units identified as basaltic flows, and a basal metafelsite unit, identified as an ash flow. The nearby St. Alphonse gabbroic plug has tectonized margins, indicating a pre-deformational (Acadian) age, and seems to be related to pre-Acadian White Rock metavolcanics.

Petrographic examination of the metavolcanics reveals them to be pervasively altered, sheared, and metmorphosed to the lower greenschist facies. Primary titanaugites survive in the uppermost metabasite unit and are petrographically and chemically similar to those of the gabbroic plug.

Examination of the major, minor, and trace element geochemistry of the metavolcanics and the gabbro was undertaken in order to determine the original nature of the metavolcanics, and their paleotectonic setting. Major element mobility (particularly the alkalis) was found to be significant, and therefore their use as paleotectonic discriminator elements is limited. However, some of the trace elements (REE, Hf, Ta, Th, Ti) are found to be relatively immobile.

The rare earth elements (REE's) show the metabasites to be the metamorphosed equivalents of alkali basalts, and the basal metafelsite to have rhyolitic affinities. Other trace element and minor element discriminators (Hf-Ta-Th, $TiO_2-P_2O_5$, $K_2O-P_2O_5-TiO_2$) reveal that the metavolcanics have been erupted in a within-plate continental environment. Trace element geochemistry of the St. Alphonse gabbro and pyroxene chemistry indicates it to be geochemically related to the metabasites, but slightly more evolved.

Trace element similarities between the Cape St. Mary metavolcanics and those in the Yarmouth syncline suggest the possibility of correlation on a geochemical basis. Correlations of the more evolved metabasites of the upper parts of the White Rock at Yarmouth to the Cape St. Mary exposures suggest that the gabbro is most likely a feeder for equivalent metavolcanics which once occurred at Cape St. Mary.

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CHAPTER I - INTRODUCTION AND GEOLOGIC SETTING

Introduction

The Silurian White Rock Formation of southeastern Nova Scotia is composed of quartzites, slates, siltstones, and metavolcanics, which overlie the thinly laminated grey and black slates of the Halifax Formation. At Cape St. Mary, the underlying Halifax Formation and 156 meters of the lower part of the White Rock Formation are exposed on the north limb of a southwest plunging syncline.

The occurrence of volcanic and shallow-water sedimentary rocks of the White Rock Formation above the deep-water sedimentary rocks of the Halifax Formation record a drastic change in the paleotectonic environment of southern Nova Scotia. The prevailing tectonics will control the style of sedimentation, the types of sedimentary rocks produced, and will also control the style of volcanism and the resultant volcanic rocks. The effect of the prevailing tectonics will be greatest on the igneous rocks, as tectonic environment appears to control the type of material melted, the degree of partial melting, and the amount of differentiation. Thus, the tectonic environment will strongly influence the geochemistry of igneous rocks formed in the environment. Igneous rocks geochemistry may therefore be used to discriminate between various tectonic environments, provided the ig~~en~~NEous geochemical characteristics of the various environments are known.

A variety of geochemical discriminating techniques have been proposed and tested, e.g., Winchester and Floyd (1977), Winchester and Floyd (1976), Pearce et al. (1975), Ridley et al. (1974), and Wood (1980).

It is hoped that an examination of the geochemistry of the volcanic rocks at Cape St. Mary will shed some light on the tectonic framework of southern Nova Scotia during the Lower Paleozoic.

Previous Work

E. R. Faribault (1918) first mapped western Nova Scotia for the Geological Survey of Canada, and more recent reconnaissance geological mapping has been conducted by various geologists of the G.S.C., notably Crosby (1962), Smitheringale (1960, 1973), and Taylor (1965, 1967, 1969). Tectonics of southern Nova Scotia have been examined by Keppie (1977), and regional structures were described by Fyson (1966) and Taylor (1967, 1969).

A detailed examination of the stratigraphy and paleoenvironment of the White Rock Formation was undertaken by Lane (1980), of Dalhousie University. Sarkar (1978), examined the petrology, geochemistry, and origins of the metavolcanics occurring in the Yarmouth syncline.

Geologic Setting

The bedrock of southern Nova Scotia consists entirely of Lower Paleozoic rocks, the oldest belonging to the Meguma Group of possible Cambro-Ordovician age (Table 1.1).

TABLE 1.1

PHANEROZOIC TIME SCALE (m.y.)	ERA	PERIOD	SERIES	STAGE	ROCK UNITS (MEGUMA BLOCK)
359	Paleozoic	Devonian	Upper	Frasnian	
			Middle	Givetian	Granite
370				Eifelian	- ? - ? - ? -
374			Lower	Emsian	
390				Siegenian	Torbrook
395				Gedinnian	
		Silurian		Ludlovian	New Canaan Kentville
				Wenlockian	
430 440				Llandoverian	
		Ordovician	Upper	Ashgillian	White Rock
				Caradocian	
			Middle	Llandeilian	
				Llanvirnian	- ? - ? - ? -
500			Lower	Arenigian	Halifax
				Tremadocian	
		Cambrian	Upper		- ? - ? - ? - Goldenville - ? - ? - ? -
			Middle		

Stratigraphy of the Meguma Zone of Southern Nova Scotia. (Time scale after Geologic Society Phanerozoic Time Scale 1964; rock units after Poole, 1971).

The Meguma Group is composed of two conformable and partly coeval formations. The lower Goldenville Formation consists of alternating layers of quartzite and minor slates, and the upper Halifax Formation consists of dark grey slates and minor quartzites. Harris and Schenk (1976) indicate that these lithologies of the Meguma Group represent a number of environments of deposition, including distal turbidite fan, basin plain, interchannel areas of the inner fan, continental rise, slope, and outer shelf. The base of the Meguma Group is not exposed, thus a thickness of 9.2 kilometers stated by Schenk (1971), is regarded as a minimum. Faribault (1918) recorded a thickness of at least 5,600 meters for the Goldenville Formation, and about 4,400 meters has been recorded for the Halifax Formation (Malcolm, 1929, and Taylor, 1967, _in_ Keppie, 1977).

Fossils only occur sparingly in the Meguma Group, and when found are often poorly preserved. A few occurrences of the graptolite DICTYONEMA FLABELLIFORME (EICHWALD) in the Halifax Formation slates indicate a Tremadocian age (Crosby, 1962), and poorly preserved graptolites (probably (DIDYMOGRAPTUS) are found at one locality of the Goldenville Formation, which gives that formation a possible Arenigian age (Schenk, 1970, Poole, 1971). Radiometric age dating of the Meguma Group is complicated by the regional metamorphism, however; muscovites that have been interpreted as being detrital in origin give K-Ar ages of 476 ± 19 Ma and 496 ± 20 Ma for the Goldenville metawackes (Schenk, 1970, Poole, 1971).

These faunal and radiometric data suggest that much of the Meguma is Lower Ordovician in age, however, Cambrian and Middle to Late Ordovician strata may be represented as well, although this is as of yet unsubstantiated (Harris and Schenk, 1971).

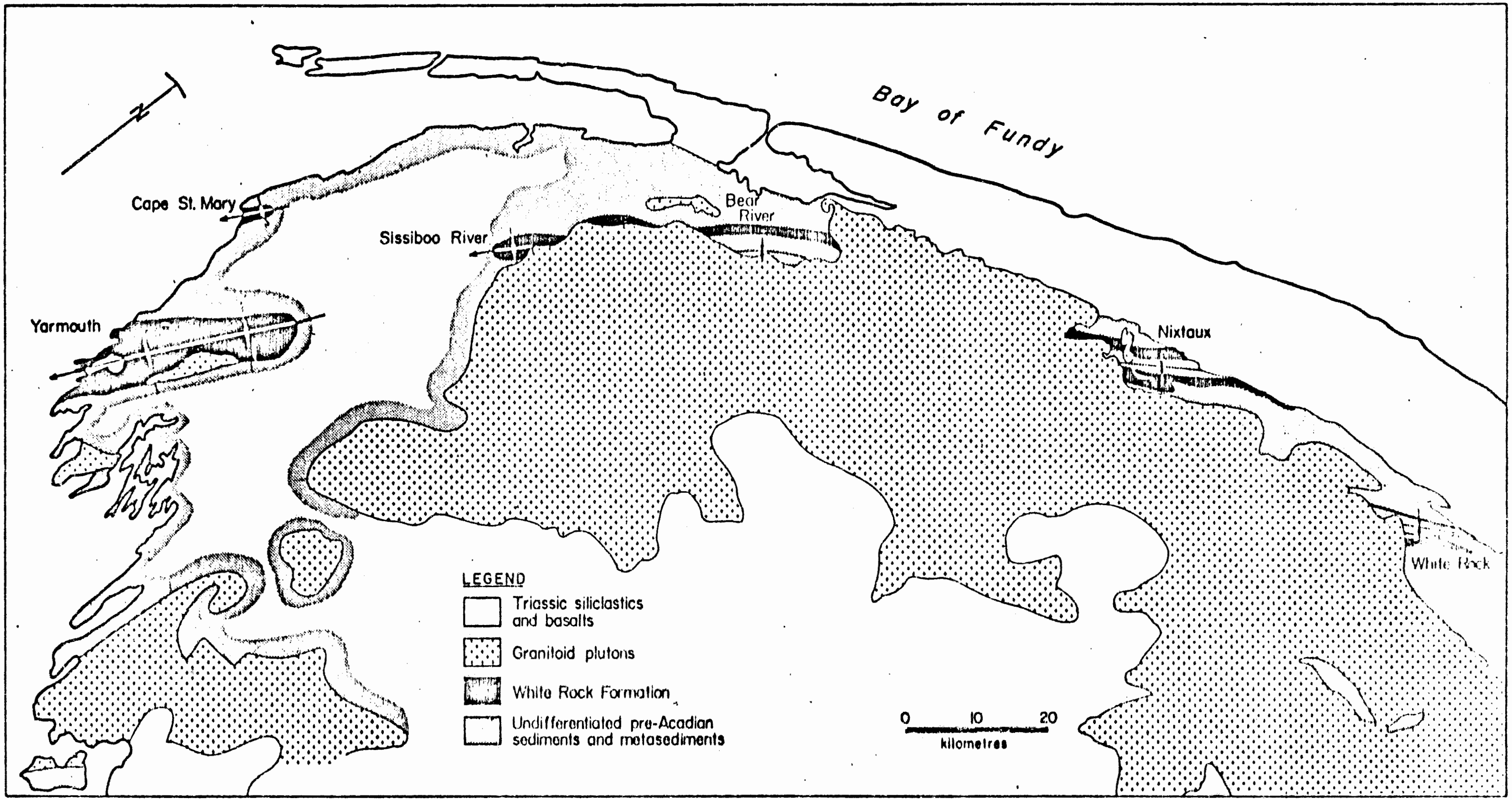
Overlying the Halifax Formation in southern Nova Scotia is the White Rock Formation, which was first defined by Crosby (1951), as "essentially two massive quartzite beds with slate between them. The top of the upper quartzite bed and the base of the lower quartzite bed are the limits of the formation." This definition is based upon the type locality for the formation at White Rock Mills, where the only distinctive rock types are the massive quartzites, the slates being indistinguishable from those of the Halifax Formation. In order to include the volcanics in the White Rock Formation, rather than the Halifax Formation, Smitheringale (1960a) redefined the White Rock-Halifax contact as being "...either at the bottom of the lowest quartzite or volcanic member, or at the top of the thinly interlaminated, light and dark grey "Halifax type" slates, whichever location is stratigraphically the lower."

Outcrops of the White Rock Formation are found occupying the cores of regional southwest-trending synclines in a 230-kilometer long belt parallel to the Fundy and southwestern coastlines of Nova Scotia (Figure 1.I). The formation is not a simple rock unit composed of slates and quartzites as it is known in the Wolfville map-area, but a complex

FIGURE 1.1

Distribution of the White Rock Formation of Nova Scotia.

Courtesy of Dr. G. K. Muecke



rock-unit composed of diverse rock types often with little stratigraphic continuity. This makes accurate correlation, mapping, and thickness determination of the White Rock Formation along this belt very difficult. The only rock type which can be considered as characteristic of the formation is the white, or light colored, massive quartzite (Taylor, 1967). Smitheringale (1973) notes that the most distinctive White Rock quartzite, known as the "double quartzite member" is present only in the eastern exposures and is untraceable to the other exposures due to either stratigraphic pinchouts or facies change within the main part of the White Rock Formation. Any correlations based on such units would, therefore, not be entirely satisfactory, as similar quartzites occur in a variety of stratigraphic positions in the White Rock Formation, as well as in the overlying Kentville Formation.

The stratigraphic thickness of the White Rock Formation increases gradually from east to west in the Annapolis Valley, from approximately 100 meters in the Wolfville map-area to 1000 meters in the Digby map-area, and attains a maximum thickness of 4950 meters in the Yarmouth area (Taylor, 1967, 1969), where the top of the formation is not exposed. A reinterpretation of the correlation and stratigraphy of the White Rock Formation in the Yarmouth syncline by Lane (1980), and Sarkar (1978), is based upon remeasurement of the general section, and correlations of individual sections of the syncline. It was recognized that parts of the stratigraphic section are repeated along vertical faults paralleling the axis of the regional syncline. As a result, a minimum thickness of 3000 meters has been assigned to the Yarmouth syncline.

The stratigraphic thickening of the White Rock Formation from its type locality to the Yarmouth map area is due in a large part to the presence of the metavolcanic rocks, which comprise approximately 50% of the formation at Yarmouth. The predominant metavolcanic rock types are metabasites, making up approximately 85% of the metavolcanics, with metafelsites comprising the remainder. A basal metabasite unit is the stratigraphically most persistant volcanic unit, and is found near Nictaux Falls and South Tremont in the Annapolis Valley, at Cape St. Mary and in the Yarmouth syncline.

The metabasites are coarse to fine grained, grey to dark green rocks, predominantly composed of amphibole and/or chlorite.with biotite in the more metamorphosed Yarmouth syncline (Sarkar, 1978) and predominantly composed of chlorite, calcite, epidote and augite in the White Rock at Cape St. Mary and in the Annapolis Valley. Although many of the metabasites have been metamorphosed and sheared to chlorite schists, primary structures suggestive of aa flows, tuffs, and pahoehoe flows are locally preserved. These rocks are assumed to be the metamorphosed equivalents of basalts, slightly differentiated basalts, mafic pyroclastics, diabases and gabbros (Sarkar, 1978).

The metafelsites are light colored, have a considerable range in grain size and are predominantly composed of feldspars, quartz, and sericite. They are considered to be the metamorphosed equivalents of benmorites, trachytes, rhyolites, and their intrusive counterparts (Sarkar, 1978).

The most abundant metasedimentary rock type of the White Rock Formation is slate, which is virtually indistinguishable from slates of the Halifax Formation. Psammitic rocks include the distinctive "White Rock quartzites", micaceous quartzites, and feldspathic quartzites. Metaconglomerates within the dominant volcanic succession of the Yarmouth syncline constitute a significant part of the metasedimentary rocks, and locally attain great thicknesses (Sarkar, 1978). These rocks have been classified as epiclastic volcanic conglomerates because they are mainly comprised of clasts derived by mechanical weathering of the underlying volcanic and sedimentary ROCKS ~~lithologies~~ (Lane, 1980). Changes in clast lithology and in matrix lithology of the metaconglomerate units reflect the reverse of the underlying stratigraphic succession, suggesting that these mass flow deposits probably formed in response to local uplift and erosion (Muecke and Clarke, 1980).

The contacts of the White Rock Formation with the underlying Halifax Formation and the overlying Kentville Formation appear to be broadly conformable. However, the lower contact, which is particularly well exposed at Cape St. Mary, has been the subject of considerable controversy. The controversy is generated by the ambiguous nature of the contact, where the axial plane cleavage is almost parallel to stratification in the Halifax Formation at one exposure of the contact at Cape St. Mary. At another exposure of the contact at Cape St. Mary, the upper few meters of the Halifax Formation are isoclinally folded with axial surfaces almost parallel to stratification in both the underlying undisturbed part of the formation, and in the overlying White Rock (Schenk, 1972). Various interpretations of the Halifax White Rock contact are: 1) A high angle unconformity of local extent (Taylor, 1965), 2) A thrust fault along which the White Rock was transported over the Meguma (Keppie, 1980), 3) A structurally modified conformable contact (Lane, 1980).

From a structural analysis of the contact, Lane (1980) concludes that: 1) absolute and unquestionable evidence of an angular unconformity does not exist, but if indeed unconformable, the contact is either only slightly angular, or is non-angular, 2) the contact could even be conformable with subsequent structural modification.

What becomes evident is that the structural modification of the contact allow for inconclusive arguments to be made for or against the unconformable and conformable interpretations of the contact.

A gradational contact is found between the White Rock Formation and the overlying Kentville Formation. The structurally conformable, and in places, gradational upper contact is difficult to define. In the Wolfville map area the slates in the upper part of the White Rock Formation are indistinguishable from those in the lower part of the Kentville Formation. Lane (1980), therefore has the contact between the two formations drawn at the top of the stratigraphically highest quartzite, which is the only distinctive lithology of the White Rock Formation in this area. Smitheringdale (1973), considers the lithologies of the White Rock and the Kentville formations in the Digby map-area to be so similar that it is not practical to separate them. Thus Smitheringdale considers the Kentville Formation as losing its identity by merging through a facies change with the White Rock Formation.

Lane (1980) considers the Kentville Formation to be definable along the Bear River exposures of the Digby map-area. A Gedinnian stage fossil assemblage defining a biozone is located approximately 257 meters above a White Rock quartz arenite unit. The biozone occurs at the lithological base of the Torbrook Formation (Jensen, personal communication in Lane, 1980), thus Lane (1980) considers the ≈250 meters of siltstones and slates found between the top of the White Rock quartz-arenite and the base of the Torbrook as the Kentville Formation.

The Kentville Formation in the central and eastern parts of the Annapolis Valley is conformably overlain by the volcanic rock — bearing New Canaan Formation of Ludlovian age. There are no distinctive rocks younger than the White Rock Formation at Cape St. Mary or in the Yarmouth syncline.

The age of the White Rock Formation is difficult to ascertain due to the scarcity of well-preserved fossils. Lane (1980, 1976) and Schenk (1972) interpret a thin, poorly stratified polymictic diamicite at the base of the White Rock Formation as a dropstone conglomerate, a product of the latest Ordovician (Ashgillian) continental glaciation episode of northwest Africa. This would place an older age limit of Late Ordovician for the base of the White Rock Formation. The only dated material from within the White Rock Formation is a brachiopod of Caradocian to Pennsylvanian age, recovered from the Yarmouth syncline. Thus, parts of the White Rock Formation are post-Middle Ordovician (Lane, 1980). Younger age limits of the White Rock Formation are primarily based upon Ludlovian fauna found in the Lower Kentville at Fales and Torbrook Rivers, and on the Gedinnian age fossils collected at the base of the Torbrook Formations at Bear River. From these faunal data, and from volcanic chronozones of the White Rock Formation, Lane (1980) concludes that the most probable age range is Late Ordovician to Upper Silurian.

Intrusive Rocks

The Lower Paleozoic rocks of southern Nova Scotia are cut by granitic intrusives, which include granodiorites, monzogranites, and leucocratic monzogranites (McKenzie and Clarke, 1975). These intrusives cut the Ordovician to Lower Devonian (Emsian) White Rock, Kentville, New Canaan, and Torbrook Formations, and are unconformably overlain by coarse subaerial clastics of the Horton Group of Lower Carboniferous (Tournaisian?) age (Clarke and Halliday, 1980). Thus, field relations show that the granitic intrusives are large post-tectonic (Acadian OROGENY) bodies intruded between Emsian and Tournaisian (?) ages. Rb-Sr isochron data give ages of 372-361 Ma, confirming the stratigraphic ages (Clarke and Halliday, 1980).

Other intrusive rocks include gabbroic plugs and sills, and spilitic sills. The most prominent mafic intrusives in the Cape St. Mary area are a diorite pluton outcropping by Wentworth Lake in Digby county, and the St. Alphonse gabbroic plug, examined in this thesis. Both bodies intrude the Meguma Group rocks, and have foliated margins and well-developed joint patterns, indicating that they are post-Meguma and at least pre or syndeformational (Acadian) in age. Other mafic bodies intrude all formations from the Halifax to the Torbrook, and when found near the South Mountain batholith are thermally metamorphosed and occasionally intruded by apophyses of granite (Smitheringale, 1973). These structural and stratigraphic data would then suggest that the main period of mafic intrusive activity for the two mafic plutons was post Meguma formation and pre- or syn-Acadian deformation, and at least pre-Emsian in age for the other mafic intrusives.

Structure and Metamorphism

An early phase of deformation as post-Tremadocian and pre-Devonian produced a set of recumbent folds, F_A, with axial plane foliation and greenschist metamorphism in the rocks of the Meguma platform (Keppie, 1977). The Lower Paleozoic rocks of southern Nova Scotia were again deformed and metamorphosed during the Devonian Acadian Orogeny, which produced upright, northeasterly trending sub-horizontal folds, F_B, with associated axial plane cleavage, and accompanied by greenschist and amphibolite facies metamorphism (Fyson, 1966, Taylor and Schiller, 1966).

The metamorphic grade of the southern Meguma platform reaches the middle upper amphibolite ~~grade~~ in the vicinity of the town of Shelburne on the southeast shore (Figure 1.2). The metamorphic grade in southern Nova Scotia falls off from the andalusite-staurolite-cordi~~a~~erite zone of the amphibolite facies in the Goldenville terrain in eastern Yarmouth County (Keppie and Muecke, 1979) to chlorite grade ~~zones~~ to the northeast and northwest. The highest metamorphic grade attained in the Yarmouth syncline is the lower amphibolite facies at the Pembroke Cove-Chegoggin Point section. The grade falls from west to east to greenschist-amphibolite transition facies seen in the area between Overton West and Yarmouth airport (Figure 1,2), (Sarkar, 1978).

Scope and Objectives

The basic aim of this thesis is to ~~fully~~ characterize FULLY the metavolcanic rocks which occur in the White Rock Formation exposed at Cape St. Mary. In the past, they have been described as "greenstones", mafic tuffs, chlorite schists, and basic volcanic rocks. Field work consisted of a total of seven days of mapping, measurement, and description of the stratigraphic column, and detailed rock sampling. Petrologic descriptions are based on approximately 50 thin sections, electron microprobe analysis of clinopyroxenes were conducted on four polished thin sections, and major element, trace element, and rare earth element studies were conducted on six carefully selected ~~geochemical~~ samples.

The objectives of this thesis are:

1) To define the field occurrence and petrology of the metavolcanics at Cape St. Mary in an attempt to establish their original nature.

2) To describe the type and grade of metamorphism and alteration of the area.

3) To conduct a whole-rock geochemical study of major, minor, and trace elements of the metavolcanics and the St. Alphonse gabbroic plutons, in an attempt to determine a

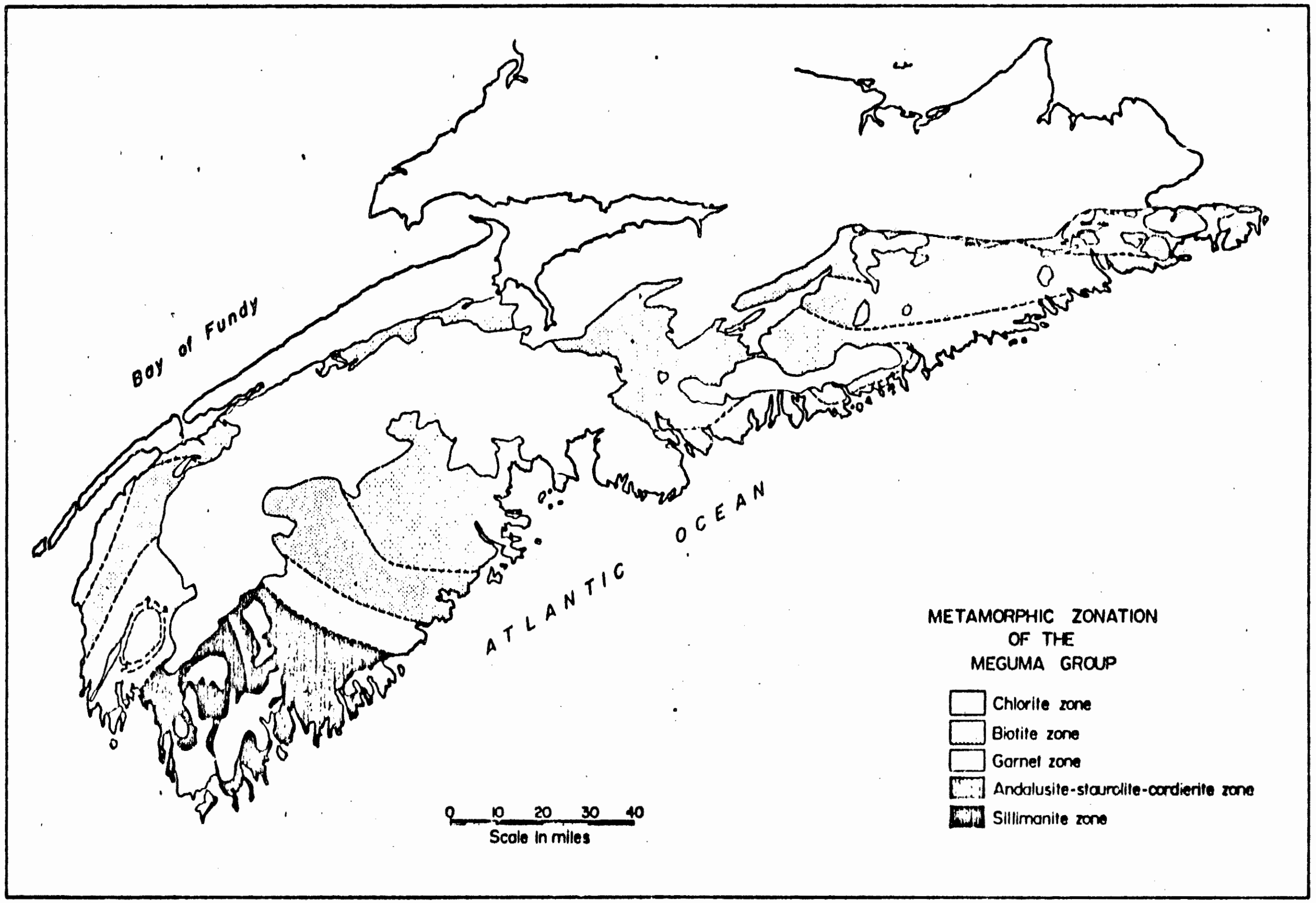
magmatic parentage of the rocks and to establish any geochemical affinities between the metavolcanics and the gabbro.

4) To correlate the petrologic and geochemical findings of this thesis to those obtained for the White Rock metavolcanics in other areas and to attempt to reconstruct the paleotectonic environment at the time of their formation.

FIGURE 1.2

Progressive metamorphic zones of the Meguma Zone, Mainland, Nova Scotia.

Courtesy of Dr. G. K. Muecke



CHAPTER II - STRATIGRAPHY AND PETROGRAPHY

Introduction

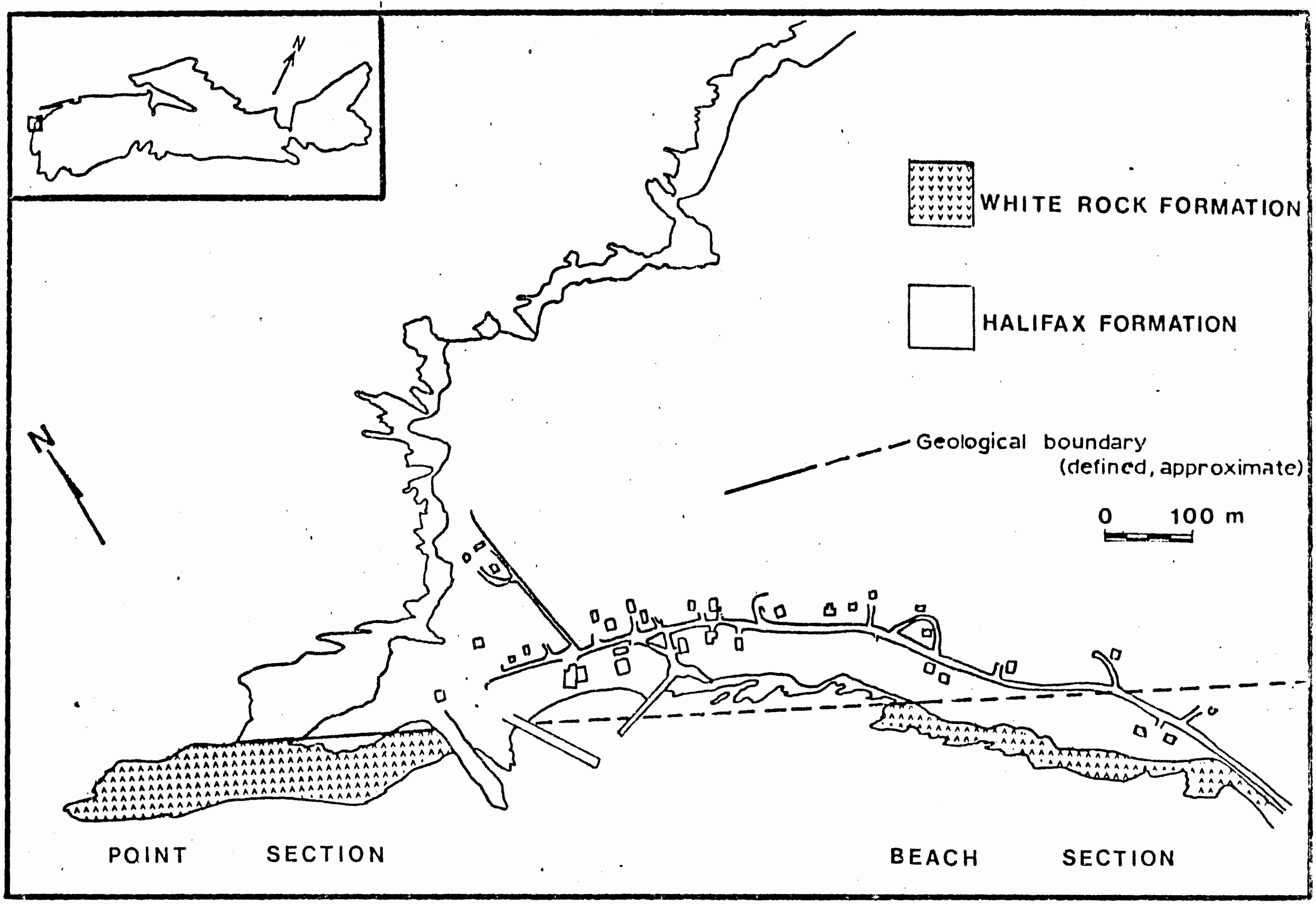
Two excellent exposures of the White Rock Formation are found at Cape St. Mary; 45 meters of section is exposed at the Point, just north of the government wharf, and 156 meters of section is exposed along the north side of Mavillette Beach (Figure 2.1). These are the only exposures of the White Rock Formation at Cape St. Mary and they are confined to the north limb of a syncline which plunges approximately 37 degrees to the southwest. The lithology of the two sections given in Figure 2.2 includes metafelsites, metabasites, metaquartzites, slates, and interbedded metaquartzites and slates.

Access to the exposures is excellent and both sections are adjacent to a paved two-lane road running from the village of Mavillette to the village of Cape St. Mary. The gabbro plug examined in this thesis is found in the village of St. Alphonse, about 3.5 kilometers north along trunk route number 1 from Mavillette (refer to geologic map in back pocket). Access to the plug, which is periodically used as a quarry, is provided by a short dirt track on the east side of the road.

Physiography

The area dealt with in this thesis and in adjacent areas consist of fairly low ground seldom exceeding 40 meters of elevation, with a thick glacial till cover. The till blanket and the numerous brackish swamps result in extremely sparse outcrop. This is especially evident at Cape St. Mary, where the only exposures occur along the sea cliffs and on the points. A harsh wet climate and the poor glacial soils result in the growth of low, thick, coniferous forests and the formation of extensive bogs.

FIGURE 2.1

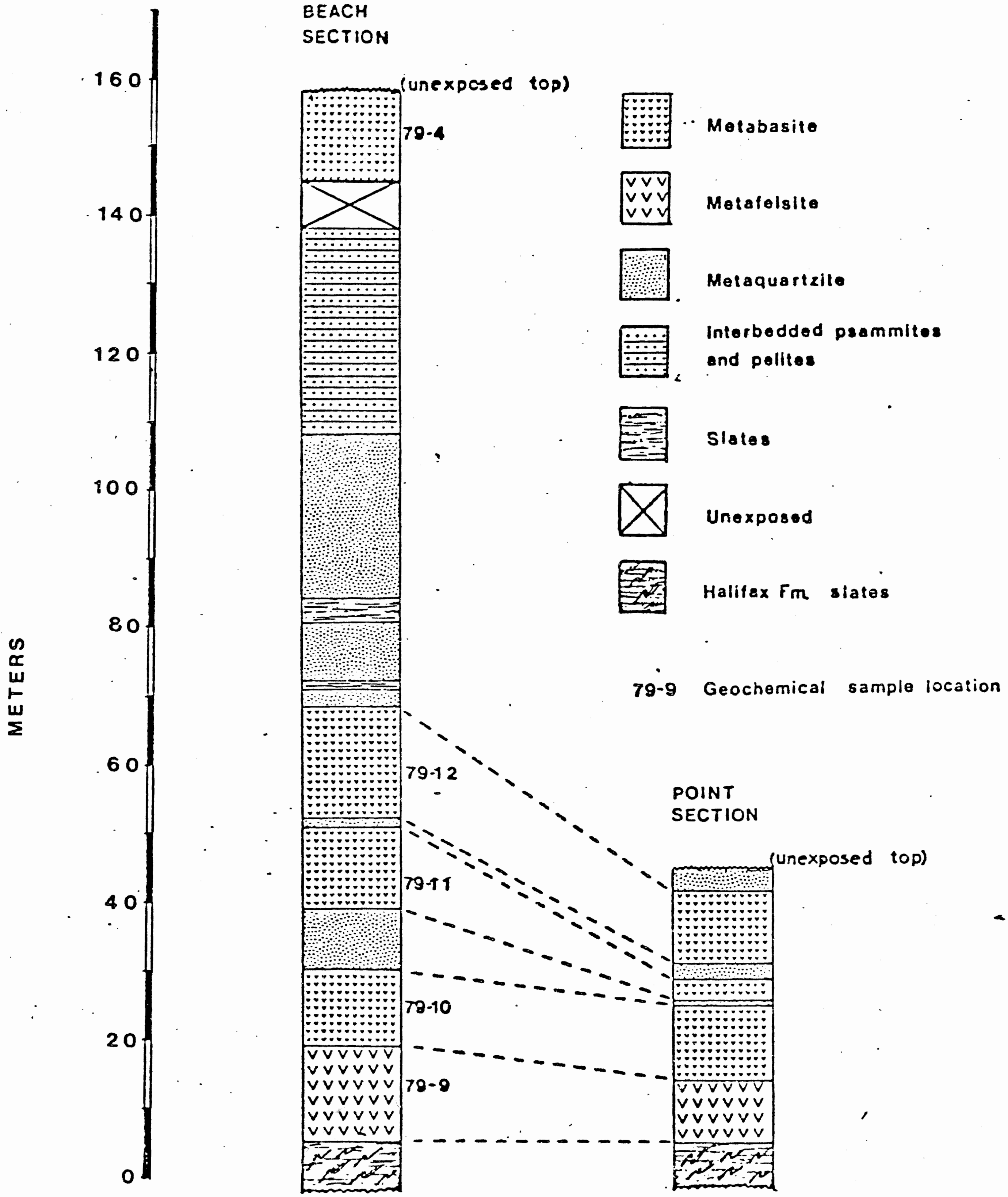


The White Rock Formation exposed at Cape St. Mary.

Diagram modified after Lane (1980).

Stratigraphy of the White Rock Formation at Cape St. Mary

FIGURE 2.2



METAFELSITE UNIT

Field Characteristics

The metafelsite unit at Cape St. Mary is pale yellow-white to rusty orange in color, schistose, and deeply weathered. It ranges from 12 meters in thickness at the Beach section to 8 meters at the Point section. Notable in the unit are small, lensoidal, pale-grey inclusions aligned parallel to the schistosity. These inclusions seldom exceed 4 centimeters in length and .5 centimeters in thickness, and persist throughout the unit, but are more numerous in the lower few meters. The origin of the inclusions is not certain, but in thin section they appear as lens-like recrystallized patches of quartz, and they could represent either flattened and stretched out pumice fragments, or quartz-filled vesicles.

The basal parts of the metafelsite are finer grained than the upper parts, and contain long thin pale-yellow mylonitic bands, suggestive of strong shearing along the metafelsite contact with the Halifax Formation (Photograph #1).

Occasional yellow sub-angular metaquartzite clasts up to 10 centimeters in diameter are found in the lower portions of the unit as well as the numerous small, lens-like, pale-grey inclusions.

Carbonate and quartz amygdules are common in the metafelsite, especially towards the top of the unit reaching up to 10 centimeters in length. They are generally subelliptical to fairly irregular in shape, but are usually aligned parallel to the schistosity.

Petrography

The dominant mineral phases found in the metafelsite are albite, and lesser amounts of K-feldspar. Both occur as .3 to 2.5 millimeter allotriomorphs. Allotriomorphs of quartz are much rarer; quartz is usually found as small, recrystallized lensoidal patches. Quartz is also found as p~~lo~~olygonal grains in pressure shadows on either side of the larger feldspar allotriomorphs.

Feldspar allotriomorphs are generally sub-euhedral and strained to some degree, the K-feldspars showing slightly deformed microcline twinning, and occasional crushed grain edges. Albite frequently displays discontinuous deformation lamellae and slightly curved growth lamellae. Quartz allotriomorphs display strong undulose and zone extinction (Photograph #2).

Small crystal plus carbonate aggregates can be seen in thin section, ranging from less than 1 millimeter to 6 millimeters in diameter. These bodies are extensively calcified, the fine-grained calcite apparently replacing euhedral and sub-euhedral crystals. Some of these crystals contain small amounts of sericite, indicating that they were originally feldspars which were sericitized then calcified. Also found in the crystal aggregates are numerous, small, generally equant opaque grains, and unaltered, euhedral, lath-shaped apatite grains, up to 5 millimeters in length.

The groundmass of the metafelsite unit is composed of very fine-grained quartz and feldspars, sericite flakes, minor chlorite, accessory apatite needles, and sphene. Although the quartz and feldspars are very fine grained, the grain boundaries can be seen to be irregular, and usually sutured. Continuous and discontinuous branching wavey sericite bands define the schistosity and occur in variable amounts throughout the metafelsite. The numerous mylonitic bands common in the lower few meters of the unit are almost wholly composed of sericite (Photograph #3).

Identification of the original nature of the metafelsite unit is made difficult by the strong shearing, pervasive alteration and weathering, which have all operated to mask or obliterate the original features. The absence of sedimentary structures and the presence of amygdules and feldspar allotriomorphs confirm an igneous origin for the unit. However, distinguishing the unit as an ash fall, an ash flow, or as a rhyolite flow, is complicated by the deformation and alteration. The fine-grained mylonitic basal zone of the metafelsite, various clasts, amgydules, and the general absence of bedding and other sedimentary structures must all be considered in attempting to decide the mode of origin of the metafelsite unit.

Features commonly associated with the ash fall deposits are prominent stratification, and graded beds. Although these features are not seen in the metafelsite, continued flow and post depositional shearing of acidic tuffs may result in the stretching and distortion of the pyroclastic fragments until they become difficult to distinguish from rhyolites with flow structure (Moorehouse, 1959).

Petrographic criteria by which altered tuffs may be recognized (Moorehouse, 1959), and their application to the metafelsite unit are:

1) Glass shards, both as unaltered glass and as devitrified glass or otherwise altered pseudomorphs of shards. Flattened shards welded together are typical of welded tuffs.

This criterion is of no use as devitrification, crystallization, alteration, and shearing of the groundmass would have long since obliterated any glass shards of the unit.

2) Porous character of the rock either primary or resurected by leaching of carbonate or preserved by carbonate fillings.

This feature does apply to the metafelsite, as the unit is extensively calcified.

3) Angular fragments of crystals often with bits

of matrix adhering to them.

This criterion does not appear to apply to the unit, as the allotriomorphs generally appear unbroken, although strained. However, recrystallization and alteration may have operated to produce the unbroken appearance of the allotriomorphs.

4) Flow structures, if present, do not form continuous flowing lines but show varied orientation, usually separated by areas without flow structure.

This does not appear to be applicable to the metafelsite, as neither obvious flow structures nor bedding occur in the unit. Again, the post-depositional processes, especially shearing, may have obliterated any such structures.

5) Fragments with varied texture and/or mineralogy in a fine-grained matrix.

Lithic fragments are conspicuous in the metafelsite both megascopically and microscopically. As mentioned previously, the numerous pale-grey, lensoidal inclusions would represent either flattened and sheared pumice fragments, or quartz-filled vesicles. The small crystal aggregates seen in thin sections most likely are igneous xenoliths, due to the presence of euhedral apatites, partially resorbed opaque grains, and altered feldspar crystals.

These criteria evidently cannot be used with great confidence in attempting to classify the metafelsite as a tuff, since alteration, metamorphism, and deformation have all been extensive. It should be noted that while criteria 2 and 3 do apply to the unit, these criteria are equally applicable to ash flow deposits.

Walker (1971) lists unit heterogeneity, recognition of a well-sorted basal layer, and discontinuous nature of stratification as some criteria which can be used to identify ash flow deposits. The fine-grained well-sorted mylonitic basal portions of the metafelsite could have resulted from the rapid deposition and freezing of the basal portion of an ignimbrite. Although the pale-grey inclusions (pumice fragments?) are found throughout the metafelsite, they are more numerous in the lower portion, suggesting they may have been concentrated and transported in the dense lower portions of an ash flow.

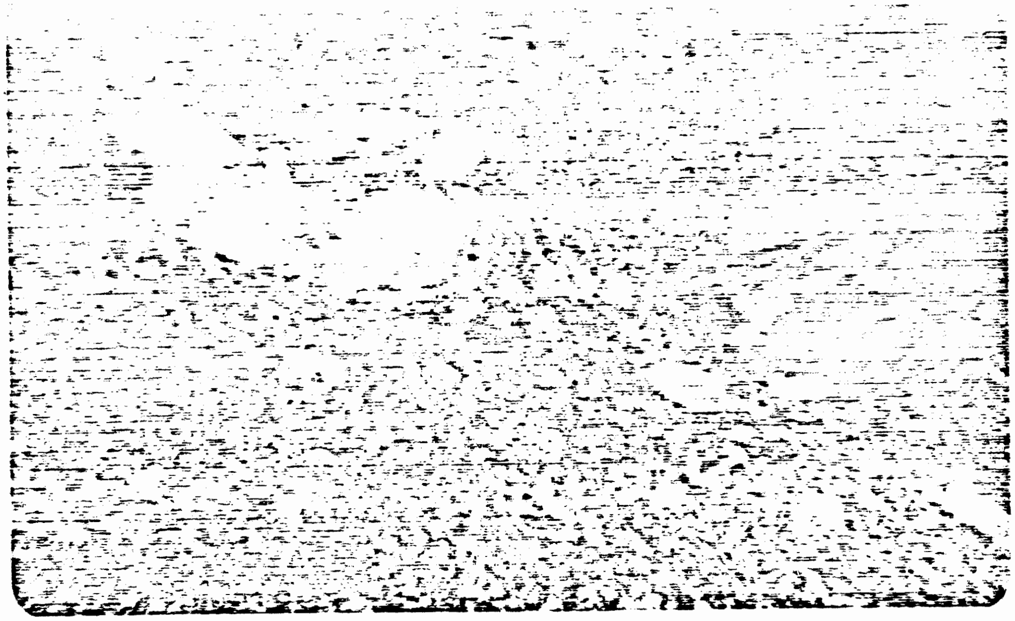
The amygdu~~lar~~ upper portion of the unit is suggestive of an originally vesiculated rhyolitic flow top. Vesiculation is also known to be a fairly common phenomenon of ash-flow tuffs, produced by release of volatiles upon devitrification (Ross and Smith, 1961). It could thus be argued that the amygdules present in the metafelsite unit formed from infilling of devitrification-derived vesicles.

While it is clearly evident that any original features of the metafelsite unit have been subjected to considerable modification, the features discussed are most suggestive of an original ash-flow nature.

Further evidence for an ash-flow origin of the metafelsite unit is the geographic distributions of the unit in the various White Rock exposures. Ash flow deposits characteristically can cover large areas. In the western United States, Smith (1960), noted ash flow deposits with lengths from 6 to 128 kilometers. Welded ash flows at Lake Toba in Sumatra cover an area of 25,000 km^2, and ash flows in the Taupo-Rototrua district of New Zealand cover 25,900 km^2 (Vlodavetz, 1966). It is thus quite reasonable that an ash flow could cover the area from the northernmost occurrence of the metafelsite unit at Fales River, to the most southerly occurrence in the Yarmouth syncline. Stratigraphic correlation of the unit throughout the White Rock Formation by Lane (1980) is supported by the description of the metafelsite unit occurring in the Bridgetown and Gaspereau map-areas by Smitheringale (1973). The macroscopic and microscopic descriptions of this unit as it occurs along the Fales River, are very similar to the description of the unit at Cape St. Mary, with the exception that partially fused glass shards are recognizable in places at the unit at Fales River. From this feature, and from the criteria normally cited as suggestive of an ash-flow nature of the unit, Smitheringdale (1973) suggests that the metafelsite is a terrestrial deposit probably formed by an ash-flow.

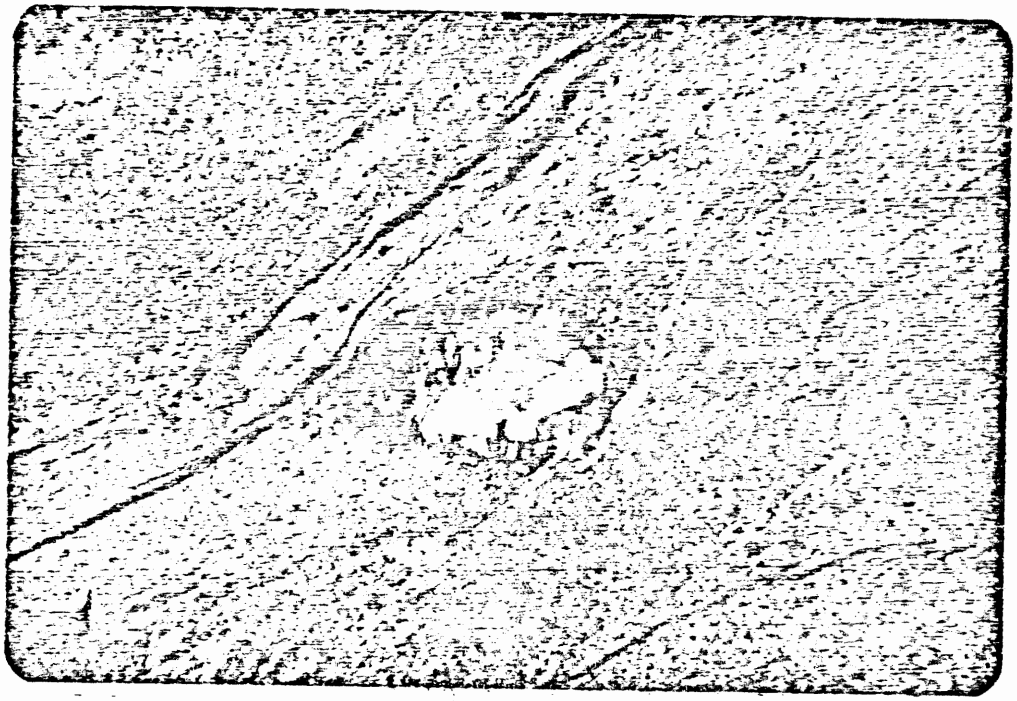
Photograph #1 - Halifax/White Rock contact exposed in the Beach section at Cape St. Mary.

The dark grey slates in the foreground are of the Halifax Formation, and are overlain in a slight (?) angular unconformity by the basal metafelsite unit of the White Rock Formation. The grey streaks in the Halifax slates have been attributed to weathering of the slates prior to the White Rock deposition (Taylor, 1969).



Photograph #2 - Photomicrograph of a thin section from the center of the basal metafelsite unit, showing partly fragmented albite allotriomorphs in a quartz-feldspar-calcite-sericite matrix.

CROSSED NICOLS. SAMPLE 79-9. ENLARGEMENT x 45.



Photograph #3 - Photomicrograph of a highly strained albite allotriomorph in a sericite rich groundmass. Thin section from the highly sheared, mylonitic basal portion of the metafelsite unit.

CROSSED NICOLS. SAMPLE AK-11. ENLARGEMENT x 45.

METABASITE UNITS A and B

Field Characteristics

The two lower metabasite units at Cape St. Mary are both approximately 12 meters thick and are very similar to each other in petrology and geochemistry. The units are grey-green in color, clearly show vesiculated upper portions, and have a well-developed cleavage. The vesiculated and amygduloidal flow tops weather to a schistose, rubbly, brown rock containing occasional irregularly-shaped amygdular metabasalt fragments.

Petrography

Thin sections reveal the two lower metabasites to be highly altered and sheared, and comprised of very fine-grained chlorite, sericitized feldspars, opaques, quartz, epidote, sericite, and minor sphene and apatite. The groundmass is composed of approximately 75% chlorite and amorphous green translucent material, 20% finely granulated feldspars and quartz, and carbonate in variable amounts. Amygdules are lensoidal in shape, being aligned with schistosity, and are usually composed either entirely of fibrous green chlorite, or of chlorite plus carbonate and recrystallized quartz. Occasionally, amygdules are composed entirely of recrystallized quartz.

Albite and quartz are the most common allotriomorphs, ranging from .1 to .5 mm in size, displaying moderate undulose extinction, and frequently showing granulated grain borders. Also present, are smaller, granulated allotriomorphs replaced by epidote.

METABASITE UNIT C

Field Characteristics

Unit C is a 16 meter thick, greenish-grey and highly sheared metabasite, with a vesiculated and amygdaloidal, chaotic upper portion. The upper part of the unit contains sub-angular xenoliths of massive grey metaquartzite, which range up to .3 meters in diameter, and ellipsoidal to irregularly shaped blocks of vesiculated basalt (Photographs #4 and #5). The middle and lower portions of the unit are more massive, containing fewer amygdules, and are less fissile and weathered than the upper portions.

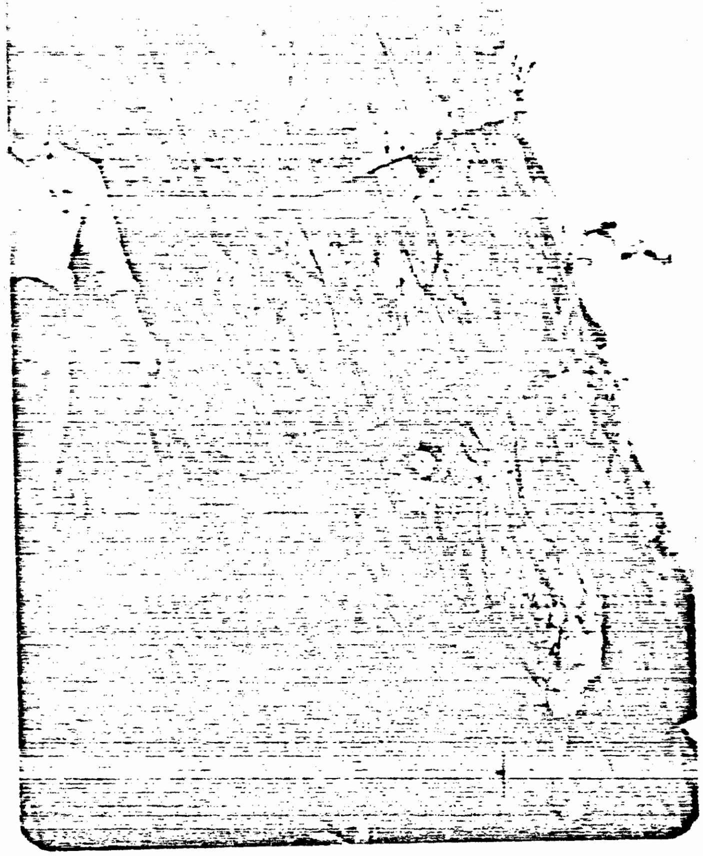
Petrography

Microscopic features show this metabasite to be somewhat more altered than the lower two metabasites. Calcification appears to be more prevasive, with relict albite allotriomorphs after plagioclase microlites remaining as the only microscopic primary igneous features (Photograph #6). Highly altered allotriomorphs of albite and quartz also occur, but are very rare. The lower portions of the unit are extremely fine-grained, and composed of chlorite, patchy calcite, opaques, amphorous dusty green material, and finely-ground feldspar and quartz. The upper portions of the unit appear less calcified, and contain in the groundmass sub-euhedral lath-shaped microlites of albite (after plagioclase) which comprise up to 60% of the groundmass. The microlites are all aligned and generally show somewhat indistinct grain edges. Amygdules are most frequently composed of either chlorite, or of chlorite plus calcite, and are all elliptical in shape.

The sub-angular xenoliths of grey quartzite are composed mainly of fine-grained sub-rounded quartz and occasional opaque grains. When visible in thin section, the contact of the metaquartzite xenoliths with the metabasite groundmass shows a very narrow reaction zone in the metabasite, composed largely of opaque matter, and tiny albite microlites (Photograph #7). The reaction zone could be a metasomatic effect caused by chemical disequilibrium of the xenoliths with the metabasite, or it could be a chill zone. If the reaction zones are the result of chilling of the metabasite, then it is possible that the metaquartzite blocks were slumped onto the flow, where they would tend to float because of their lesser specific gravity.

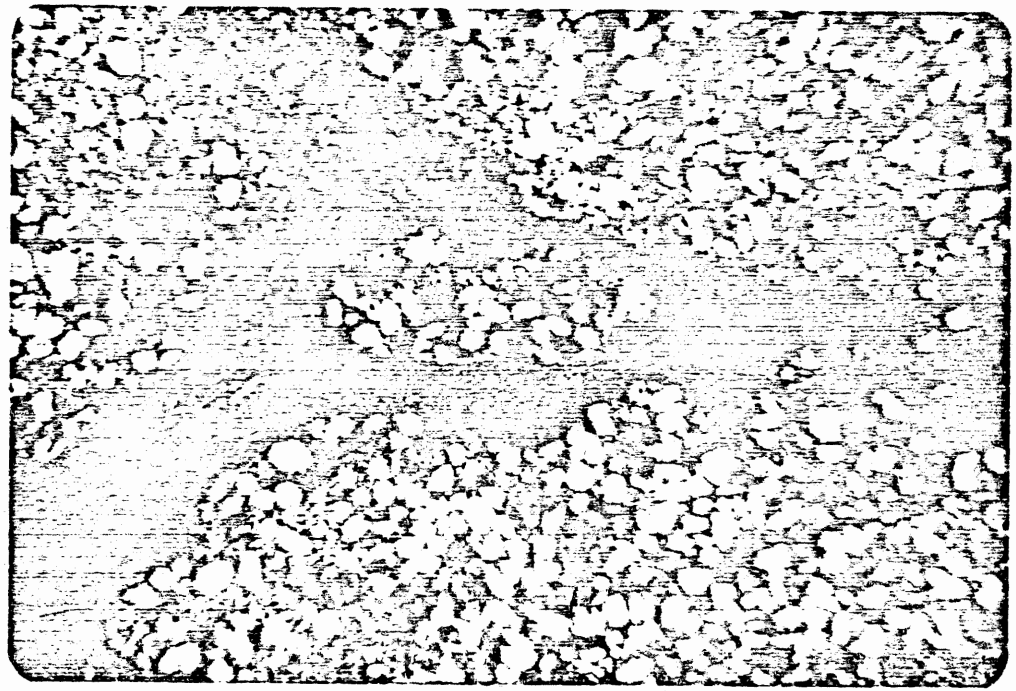
Photograph #4 - Photograph of the chaotic upper portion of metabasite unit C. Note the medium grey metaquartzite xenoliths (?) and carbonate amygdules in the darker grey vesicular metabasalt. The xenoliths (?) range up to .5 meters in length.

Photograph #5 - Close-up photograph, clearly illustrating the vesicles in the upper portion of metabasite unit C. Vuggy nature of metabasite due to leaching of carbonate from filled vesicles.



Photograph #6 - Photomicrograph showing the relict igneous texture of the aligned albite allotriomorphs after plagioclase microliths. Thin section from the middle portion of metabasite unit C.

CROSSED NICOLS. SAMPLE 80-B. ENLARGEMENT x 80.



Photograph #7 - Photomicrograph showing the narrow, dark colored "chill" margins surrounding sub-rounded metaquartzite xenoliths of the upper portion metabasite unit C.

CROSSED NICOLS. SAMPLE 80-T. ENLARGEMENT x 1.8.

METABASITE UNIT D

Field Characteristics

The uppermost metabasite unit in the section is markedly different from the others, both megascopically and microscopically. It is partially obscured by the sands of Mavillette Beach and only accessible at low tide, therefore, only a minimum thickness of 13 meters can be determined. The unit is dark grey-green in color, fine-grained, and massive. No vesicles or amygdules are seen; however, the exposure is probably only of the lower part of the unit.

Petrography

The most obvious difference of this metabasite from the three lower metabasites is the presence of primary titanaugite and apatite allotriomorphs. The titanaugites generally constitute from 10 to 15% of the thin sections, and are commonly subeuhedral to anhedral, with straight edges where they have been fractured and drawn out along the schistosity. The fracturing has reduced the titanaugites to a variety of sizes, but most commonly the fragments are between 1 and 1.5 mm in diameter (Photograph #8).

The titanaugites are relatively unaltered, although when a particularly large grain has been broken up, a fibrous mass of wavey sericite, talc and chlorite occupies the fractures (Photograph #9). Minute radiating fans of muscovite-sericite frequently cluster in amongst the pyroxene fragments, and are also found as poorly developed pressure shadows on either side of the pyroxene allotriomorphs. The pyroxenes occasionally have small interior patches that have altered to kaersutite, a brown titaniferous amphibole.

Plagioclase allotriomorphs are almost completely sericitized, and have indistinct grain boundaries. Only very rarely does a plagioclase grain survive, and these are found to be andesine to oligoclase in composition. Apatite is present as long, lath-shaped phenocrysts, up to .8 mm in length, which are often broken up by shearing. Apatites are also found as inclusions in the titanaugite allotriomorphs. Approximately 1% of the thin section slides are composed of strongly resorbed, roughly rectangular and irregularly shaped opaque phenocrysts that range up to 1.2 mm in length. Some opaques consist of very dark translucent material intermixed with the true opaque material, and are most likely magnetites altering to hematite.

The groundmass of the metabasalt is largely composed of the dusty green translucent material, which is probably a mixture of chlorite, talc, sericite, and various clay minerals. No patchy calcite appears in the unit, and the amount of sericite is considerably more than what is seen in the lower metabasites. Sericite is usually associated with the pyroxenes, but also occurs in small elongate patches. Chlorite is considerably less abundant in this unit than in the other metabasites, occurring as small wisps in the groundmass, and often as an alteration product of pyroxenes.

Photograph #8 - Photomicrograph of the general texture of the uppermost metabasite, unit D. The highly birefringent angular minerals are titanaugite allotriomorphs in a matrix of chlorite, sericite, and talc. Also present are albite allotriomorphs and opaque grains (probably magnetite).

CROSSED NICOLS. SAMPLE 79-5. ENLARGEMENT x 10.

Photograph #9 - Photomicrograph of the titanaugites from unit D, clearly illustrating their fractured nature. Note the wavey sericite bands, defining the schistosity.

CROSSED NICOLS. SAMPLE 79-4. ENLARGEMENT x 45.

Identification of the metabasite units A, B, and C as basaltic flows is based upon their vesiculated and amygdaloidal upper portions, which would represent flow tops. Identification of the original igneous character of unit D, however, is made difficult by the small size of the exposure, and the absence of an exposed top. None of the criteria for identification of tuffs (see metafelsite section, page 25) can be applied to the unit, so it is unlikely to be a mafic tuff. The unit could then be a mafic sill, or the bottom (unvesiculated) portion of a basaltic flow. Evidence for either is scanty and inconclusive.

THE ST. ALPHONSE GABBROIC PLUG

Field Characteristics

The St. Alphonse gabbroic plug is an elliptical intrusion, measuring roughly 1000 meters by 700 meters (see map in back pocket), however, the contacts with the Halifax Formation are not exposed. The coarsest-grained, central part of the intrusion forms a low hill easily visible from the highway, and is periodically quarried for memorial stone. Outcrops of the intrusion away from the quarry are scarce due to the thick glacial drift.

Outcrops of the intrusion immediately outside the quarry are finer grained than the central part of the intrusion, which becomes increasingly foliated as the contact with the Halifax Formation is approached. The foliation is due to a rough alignment of the plagioclase laths, and in part to a reduction in grain size. Foliation attitudes cannot be determined due to poor outcrop. Two well-developed joint sets occur in the intrusion, striking 075 degrees and 160 degrees, with dips of 55 degrees north and 55 degrees west respectively. The foliation and jointing would indicate that the intrusion is at least syndeformational, or more likely, pre-deformational in age, giving a pre-Acadian age for the gabbro. Although no age dates exist for the intrusion, its predeformational age is clearly supported by chemical affinities to the metavolcanics at Cape St. Mary.

Petrography

The gabbro consists mainly of coarse-grained clinopyroxene (titanaugite), plagioclase, ilmenite, apatite, and variable amounts of chlorite and sericite. The clinopyroxenes have a wide size range, averaging about 2 mm in diameter, but can be as large as 8 to 10 mm in diameter in the centre of the intrusion. They are generally anhedral, but develop straight edges where they have been fractured and broken apart along cleavage planes. Clinopyroxene chemistry is treated more fully in Chapter 5 .

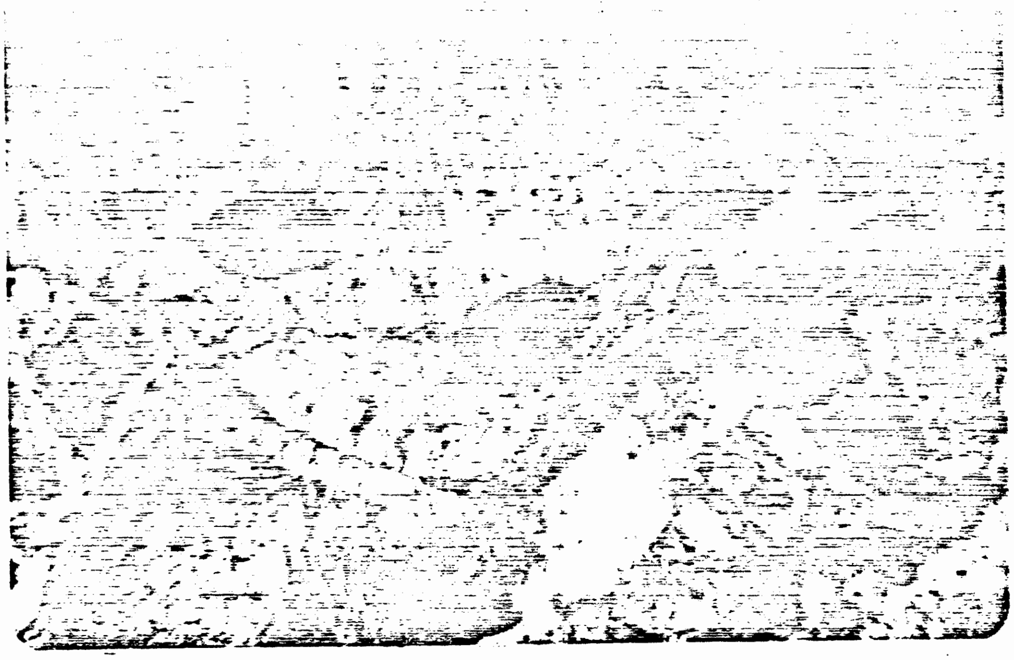
Plagioclases generally occur as sub-euhedral grains, ranging from .5 mm long inclusions, to 2 cm long cumulus crystals. Composition of unzoned plagioclases is approximately An_{50}, while zoned plagioclases range from An_{50} in the cores to albitic rims. The zoning could largely be due to overprinting of the rims by albitization.

Generally 3 to 5% of the gabbro is composed of skeletal, roughly rectangular ilmenite grains up to 1.5 mm in length, and lesser amounts of irregularly shaped magnetite grains. Accessory minerals of the gabbro include euhedral apatite grains up to 4 mm long, and minute sub-euhedral sphenes.

Coarse-grained cumulus textures characterize the central part of the intrusion, while fine to medium-grained ophitic and sub-ophitic textures are found in the marginal parts of the intrusion. The cumulate phases are long, lath-shaped, sub-euhedral clinopyroxenes, reaching up to .8 cm in length, and slightly smaller, generally zoned sub-euhedral plagioclase crystals (Photograph #10). Ophitic and sub-ophitic textures are seen in the more marginal parts of the intrusions by clinopyroxene allotriomorphs poikilitically enclosing small euhedral plagioclase laths (Photograph #11).

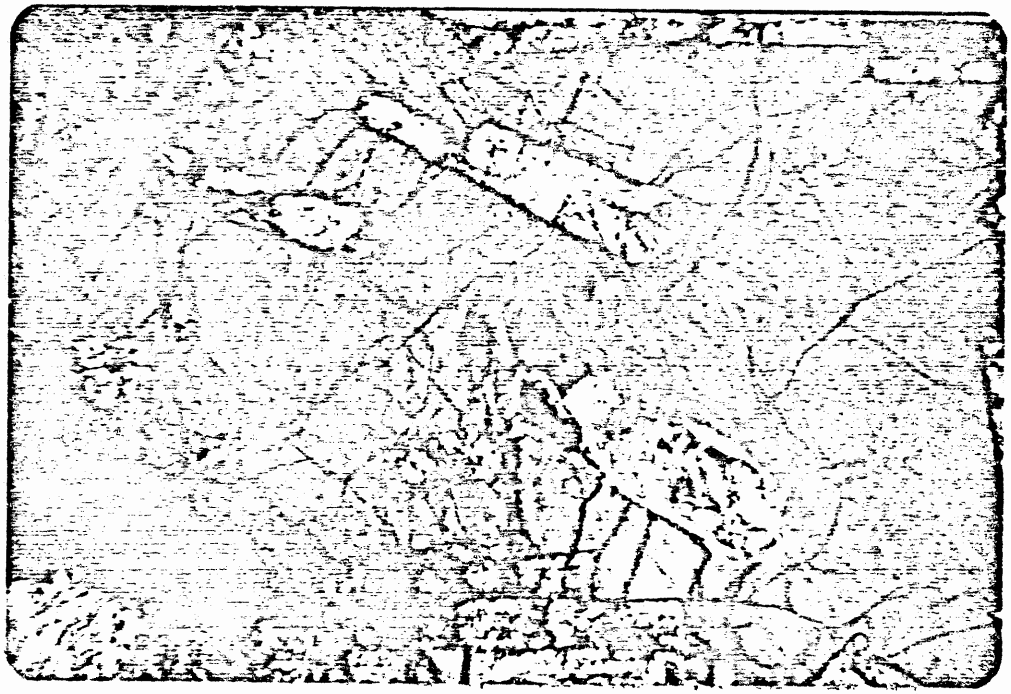
The foliated fabric of the margins of the intrusion, which is clearly visible in the field, is only weakly developed in the thin sections. The foliation as seen in thin section appears to be represented by granulation and fracturing, accompanied by an increase in alteration. Only ophitic clinopyroxenes, rare opaques, and broken apatites survive in the foliated areas. Deformation is seen in the central parts of the intrusion by slightly wav~~e~~y extinction in clinopyroxenes, occasional deformation lamellae in plagioclase, and bent and broken apatite crystals.

Alteration affects all parts of the intrusion, but is greatest in the margins. The large cumulus clinopyroxene grains are unaltered, but the fractured and broken clinopyroxene allotriomorphs in the foliated areas are often surrounded by wav~~e~~y chlorite and patchy sericite. Occasionally, small patches of amphibole develop in the centers of the larger clinopyroxene~~s~~ allotriomorphs. This amphibole exhibits strong brown pleochroism, and is probably the titaniferous amphibole kaersutite. Cumulus plagioclase grains are sericitized to varying degrees, and ~~often~~ appear to have wide, albitized rims. Sericitization in the coarse-grained areas of the intrusion is seen in outcrop as wide pale grey bands up to 10 cm. in width, in which the plagioclases have been turned to an off-white color. These bands of sericitized plagioclases surround fractures presumably along which the alteration fluids were introduced.



Photograph #10 - Photomicrograph of the cumulate clinopyroxene and plagioclase crystals, from the central part of the St. Alphonse gabbroic plug. Note the fractured and bent apatite crystals.

CROSSED NICOLS. SAMPLE 80-1. ENLARGEMENT x 45.



Photograph #11 - Photomicrograph of the ophitic texture which characterizes the more marginal parts of the St. Alphonse gabbro plug. The small, euhedral, sericitized plagioclase laths are poikilitically enclosed by a clinopyroxene allotriomorph.

CROSSED NICOLS. SAMPLE 80-D. ENLARGEMENT x 45.

METASEDIMENTARY ROCKS

Approximately 57% of the White Rock Formation exposed at Cape St. Mary is composed of psammites and metapelites. The psammites are located in the lower two-thirds of the formation, and consist of generally massive and ~~occasionally~~ cross-stratified, fine to medium-grained pale yellow-grey metaquartzites. They are predominantly composed of strained, sub-rounded quartz grains, and there is a 10 to 15% phyllosilicate matrix in some beds. These rocks are probably the metamorphosed equivalents of quartz-arenites and quartz-greywackes.

Thinly interbedded psammitic and pelitic rocks occur in the upper third of the section. Towards the top of the section, the intercalated psammitic beds decrease in number and thickness, as the number of pelitic beds increase. The psammites ~~often~~ have wav~~e~~y rippled tops, or are in lenticular beds, and the pelitic beds are usually finely laminated, and ~~occasionally~~ rippled.

The stratigraphy of the White Rock Formation and its sedimentary rocks is ~~are~~ examined in detail by Lane (1980).

METAMORPHISM

The mineral assemblages of the rocks from Cape St. Mary and the St. Alphonse plug (Table 2.1) suggest that the metamorphic grade reached the chlorite zone of the greenschist metamorphic facies. Characteristic minerals of this grade in the Cape St. Mary area are chlorite, white micas (muscovites and "sericite"), calcite, albite, and epidote. Notable absences in the mineral assemblages are biotite, amphibole, cordierite, and garnet, which are all present in the Yarmouth syncline. Sarkar (1978) concluded that the highest metamorphic grade reached in the Yarmouth area is the lower amphibolite facies. The greenschist-amphibolite transition facies was also found in the Yarmouth area. The metamorphic grade of the southwestern coast of Nova Scotia falls from the lower amphibolite facies of the Yarmouth area, to the lower greenschist facies of Cape St. Mary. The metamorphic zonation of southern Nova Scotia is illustrated in figure 1.2 .

TABLE 2.1

MINERAL ASSEMBLAGES, WHITE ROCK FORMATION, CAPE ST. MARY

	METABASITES				METAFELSITE	ST. ALPHONSE GABBRO	METASEDIMENTARY ROCKS
	A	B	C	D			
Plagioclase	−	−	+	+	−	+	−
K-Feldspar	+	+	+	+	+	±	+
Clinopyroxene	−	−	−	+	−	+	−
Chlorite	+	+	+	+	±	+	−
Sericite	+	+	+	+	+	+	±
Epidote	+	+	±	−	−	−	−
Calcite	+	+	+	−	+	−	+
Quartz	+	+	+	+	+	−	+
Opaques	+	+	+	+	±	+	+
Apatite	+	+	±	+	+	+	−
Sphene	+	+	−	+	+	+	−

CONCLUSIONS

The stratigraphy of the White Rock Formation at Cape St. Mary consists of basal metafelsite unit, identified as a probable welded ash-flow, followed by four metabasite flows interbedded with psammites and pelites. Metasomatism combined with strong shearing and weathering has almost entirely obliterated any original flow features, and has made units A, B, and C petrographically similar to each other. The uppermost mafic unit, unit D, is unique in the entire White Rock Formation, as it has the only recorded occurrence of primary pyroxenes.

The St. Alphonse gabbroic plug has alkaline affinities, as suggested by the presence of the titaniferous augites, which are characteristic of basic alkaline rocks. A similarity between the pyroxenes in the gabbro and the pyroxenes in metabasite unit D, suggests that the two units are related. This relationship is reinforced by the pre-Acadian age of the gabbro as revealed through its structure, and by geochemistry, as will be discussed in Chapters 3 and 4.

CHAPTER III - MAJOR AND MINOR ELEMENT GEOCHEMISTRY

Introduction

The metavolcanics of the White Rock Formation at Cape St. Mary are weathered, sheared, and altered to such an extent that the field and petrographic evidence presented in the previous chapter cannot unambiguously identify the original nature of the rocks. Geochemistry is a valuable tool which can provide clues as to the original nature of the rocks, and can also be used to compare units for fundamental similarities and differences. Examination of the major element geochemistry of the metavolcanics and the St. Alphonse gabbro should indicate which elements were mobile in the White Rock Formation at Cape St. Mary, and the extent of metasomatism of the rocks. It is hoped that a combination of the major element geochemistry with the trace and rare earth geochemistry will indicate the pre-alteration nature and tectonic setting of the metavolcanics.

Methods

The whole rock analyses (Table 3.1) were determined by electron microprobe on fused glasses of the samples and by ~~the~~ atomic absorption spectrometry (A.A.). The results of the analyses by electron microprobe are compared to those obtained by A.A. in table 3.1. Description of all analytical methods employed, and of the method used to

TABLE 3.1

COMPLETE WHOLE ROCK ANALYS$\overset{E}{I}$S,

COMPARED TO A.A. ANALYSES

	79-4	% DEVIATION FROM A.A.	79-6	% DEVIATION FROM A.A.	79-9	% DEVIATION FROM A.A.
SiO_2	45.22		48.12		73.71	
TiO_2	3.00	+5.7	3.22	+7.5	0.23	+20.7
Al_2O_3	14.82	-3.5	13.97	-1.5	8.86	+2.9
Fe_2O_3	3.84		4.21		N.D.	
FeO	10.27		10.00		3.10	
MnO	0.15	+33.3	0.25	+4.0	0.05	0.0
MgO	6.27	+0.8	2.59	+8.9	1.23	+5.7
CaO	8.42	-0.7	7.52	+7.1	2.11	-0.5
Na_2O	2.82	-5.1	4.14	-0.5	2.88	+5.2
K_2O	0.94	-13.8	1.49	-8.6	0.93	-7.9
P_2O_5	0.81	+25.9	1.87	+24.6	0.15	+40.0
S	0.55		0.51		0.04	
H_2O+	2.96		2.07		0.82	
H_2O-	0.08		0.25		0.19	
CO_2	0.26		N.D.		5.79	
TOTAL	100.41		100.21		100.11	
TOTAL Fe (as FeO)	13.73	+4.1	13.79	-5.5	3.10	+3.5

TABLE 3.1 continued
Complete Whole Rock Analysis,
Compared to A.A. Analyses

	79-10	% DEVIATION FROM A.A.	79-11	% DEVIATION FROM A.A.	79-12	% DEVIATION FROM A.A.
SiO_2	46.93		41.58		42.03	
TiO_2	3.81	+3.2	2.99	+13.4	2.76	+8.0
Al_2O_3	16.44	+5.1	14.92	+9.4	13.52	+3.7
Fe_2O_3	3.52		3.89		3.45	
FeO	14.62		9.25		8.61	
MnO	0.06	-45.5	0.18	+33.3	0.15	-16.7
MgO	3.40	+6.8	6.07	+7.9	5.68	-36.3
CaO	1.86	+7.0	12.07	+10.9	9.94	+2.1
Na_2O	2.16	+10.	2.63	+4.9	0.92	-6.1
K_2O	0.83	-12.6	0.76	-7.3	1.26	-11.3
P_2O_5	1.00	+23.0	0.42	+19.1	0.53	
S	0.85		0.42		0.90	
H_2O+	4.29		4.82		5.23	
H_2O-	0.32		0.10		0.51	
CO_2	0.68		0.18		4.76	
TOTAL	100.77		100.28		100.24	
TOTAL Fe (As FeO)	17.79	+6.5	12.75	+11.5	11.71	+4.6

TABLE 3.2

CHEMICAL COMPARISON OF THE FOUR METABASITE UNITS FROM THE WHITE ROCK FORMATION AT CAPE ST. MARY WITH TWO AVERAGE ALKALI BASALTS*

	79-4	79-10	79-11	79-12	Alkali Basalt Without Olivine	Normal Alkali Basalt and Dolerite
SiO_2	45.96 - 47.56	48.24 - 50.81	40.85 - 46.77	44.53 - 49.37	47.01	46.13
TiO_2	2.74 - 3.46	3.89 - 4.15	3.10 - 3.92	2.87 - 3.29	3.02	2.65
Al_2O_3	14.83 - 15.81	17.09 - 17.61	13.15 - 16.75	14.51 - 15.69	14.72	14.75
FeO	13.55 - 14.83	18.13 - 19.41	10.86 - 16.00	12.39 - 13.77	11.34	12.07
MnO	0.0 - 0.30	0.0 - 0.19	0.0 - 0.40	0.02 - 0.32	0.15	0.20
MgO	5.99 - 6.97	3.51 - 3.67	5.58 - 7.22	5.47 - 7.21	6.85	9.46
CaO	8.25 - 9.17	1.23 - 1.69	12.31 - 13.13	10.30 - 11.90	12.48	10.82
Na_2O	2.64 - 3.20	1.97 - 2.59	2.46 - 3.08	0.77 - 1.29	2.60	2.65
K_2O	0.82 - 1.12	0.80 - 0.96	0.62 - 0.98	1.13 - 1.69	1.08	0.96
P_2O_5	0.66 - 1.02	0.93 - 1.19	0.21 - 0.67	.46 - 0.72	0.37	0.39

The range of each element oxide is based on a 95% probability that the actual value lies within that range. Each metabasite element oxide probability range is based on six analyses.

*The alkali basalt without olivine is based on 22 analyses. The normal alkali basalt (and dolerite) is based on 96 analyses. Both analyses from Nockolds (1954). For ease of comparison with the White Rock metabasites, the analyses of Nockolds (1954) are recalculated as volatile free, and with Fe_2O_3 and FeO expressed as FeO.

TABLE 3.3

CHEMICAL COMPARISON OF THE ST. ALPHONSE GABBRO (79-6) WITH AN AVERAGE ALKALI GABBRO, AND THE METAFELSITE AT CAPE ST. MARY WITH AN AVERAGE RHYOLITE

	ST. ALPHONSE GABBRO (79-6)	AVERAGE* ALKALI GABBRO	METAFELSITE (79-9)	RHYOLITE+
SiO_2	48-23 - 51.01	43.65	75.92 - 82.60	73.92
TiO_2	2.76 - 3.38	2.84	0.0 - 0.56	0.28
Al_2O_3	12.71 - 15.89	14.77	8.24 - 10.82	13.47
FeO	13.30 - 16.70	11.63	2.81 - 3.67	2.48
MnO	0.18 - 0.34	0.16	0.0 - 0.16	0.06
MgO	2.21 - 3.09	9.25	1.14 - 1.50	0.40
CaO	7.13 - 8.27	12.29	2.04 - 2.50	1.16
Na_2O	3.75 - 4.73	2.30	2.42 - 3.78	3.60
K_2O	1.32 - 1.74	0.91	0.71 - 1.29	4.37
P_2O_5	1.55 - 2.27	0.44	0.0 - 0.48	0.07

* BASED ON 84 ANALYSES (NOCKOLDS, 1954).

\+ BASED ON 554 ANALYSES (LEMAITRE, 1976).

TABLE 3.4 continued

NORMATIVE COMPOSITIONS

	79-4	79-6	79-9	79-10	79-11	79-12
Q	0.00	1.74	51.85	19.46	0.00	14.26
OR	5.71	9.01	5.80	5.12	4.72	7.89
AB	24.51	35.79	25.70	19.07	14.04	8.24
AN	25.69	15.46	0.00	0.00	27.97	16.68
NE	0.00	0.00	0.00	0.00	5.04	0.00
Di	8.23	8.49	0.00	0.00	24.98	0.00
HY	16.32	11.52	8.80	25.54	0.00	22.21
OL	4.27	0.00	0.00	0.00	(0.03	0.00
Mt	5.72	6.24	0.00	5.33	5.92	5.30
IL	5.85	6.25	0.50	7.55	5.96	5.55
AP	1.93	4.43	0.37	2.42	1.02	1.30
C	0.00	0.00	3.29	12.51	0.00	5.15
CC	0.61	0.00	3.60	1.01	0.43	11.46
TOTAL	98.84	98.83	99.91	98.18	99.09	98.04

incorporate the volatiles and Fe_2O_3 into the whole rock analysis are given in the Appendix.

Discussion

The strongly altered appearance of the metavolcanics suggests that the major element geochemistry of the rocks may have changed significantly since the rocks were formed. Therefore, the effects of this pervasive alteration on the rocks must be evaluated before any conclusions about their major element geochemistry can be drawn. Any originally glassy matrix of the volcanics has long since been devitrified and replaced by chlorite, calcite, and albite, which will affect the amounts of SiO_2 and Al_2O_3. CaO is affected by the chloritization of clinopyroxene, the addition of calcite, and albitization of plagioclase, which would also affect the amount of Na_2O. The amounts of MgO in the volcanics would be affected by the alteration of any olivine which may have been present, due to the replacement by calcite and chlorite.

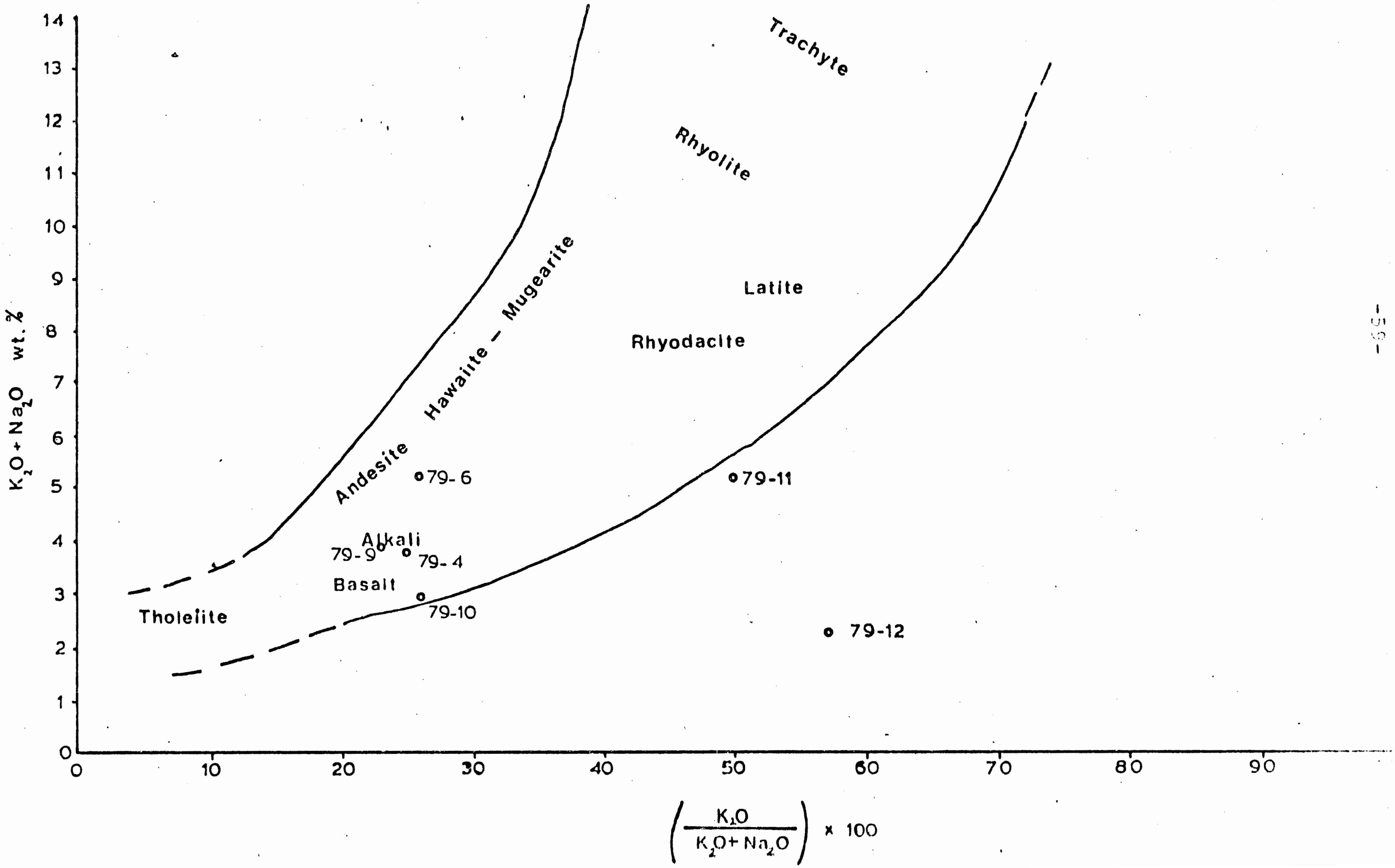
Table 3.2 shows the 95% confidence range of each element oxide in the metabasites, compared with two alkali basalts. Table 3.3 shows the same for the St. Alphonse gabbro and the metafelsite unit at Cape St. Mary, compared to an average alkali gabbro and an average rhyolite respectively. Comparison of the 95% confidence range of particular elements between the rocks allows for identification of statistically significant geochemical differences. These comparisons have been made because these rock types appear to be the closest representatives of the original nature of the metavolcanics and the metagabbro. In all three comparisons, the rocks can be seen to be broadly similar to their suspected prealteration equivalents. However, as will be demonstrated, the major elements do show some significant departures.

Significant differences between the metabasites are seen in the contents of MgO, FeO, Na_2O, and K_2O and particularly CaO. CaO ranges from a low of 1.86% in 79-10 to a high of 12.07% in 79-11 (Table3.1), which reflects the high degree of calcification of these units. Since the metabasites show a close similarity of REE patterns (figures 4.3 and 4.5) and immobile trace element contents (Chapter 4), it may be assumed that the major element geochemistry of the metabasite units was at one time less variable, (e.g. Yoder, 1978, Carmichael, Turner and Verhoogen, 1974, page 507). The major element differences between the metabasites can therefore be attributed to element mobility during metasomatism and metamorphism. Although the St. Alphonse gabbro and the metafelsite of Cape St. Mary have no units in the area to which they can be geochemically compared, it can be assumed that the elements seen as mobile in the metabasites are also mobile in the gabbro and the metafelsite. This assumption is supported in table 3.4 where significant differences in the amounts of MgO, FeO, K_2O, and CaO are seen between the gabbro and metafelsite and their respective suspected prealteration equivalents. The lower degree of alteration and shearing of the St. Alphonse plug would suggest that element mobility in the gabbro has not been as great as in the metavolcanics.

The alkali variation diagram of Hughes (1973), (figure 3.1), is not intended to differentiate between rock suites, but to show that all common fresh volcanic rocks appear to have compositions that lie within a definable spectrum. The plots of the St. Alphonse gabbro, metabasite units A and D from Cape St. Mary (samples 79-6, 79-10, and 79-4) all fall within the alkali content range expected for alkali basalts. As these units are suspected to have alkali basalt affinities from trace and REE data, alkali movement in these units may have been insignificant. However, metabasite units B and C (79-11, 79-12) fall well outside the expected alkali content range for any igneous rock; thus alkali movement in these two units may have been considerable. Alkali metasomatism was also considerable in the metafelsite, which plots in the field of alkali basalts rather than in the expected alkali range of rhyolites.

Major element mobility in the White Rock Formation was demonstrated by Muecke _et al_ (1979) for the Yarmouth syncline. It was observed that CaO, FeO, MgO, and Na_2O

Figure
~~TABLE~~ 3.1 - Alkali Variation Diagram of Hughes (1973).

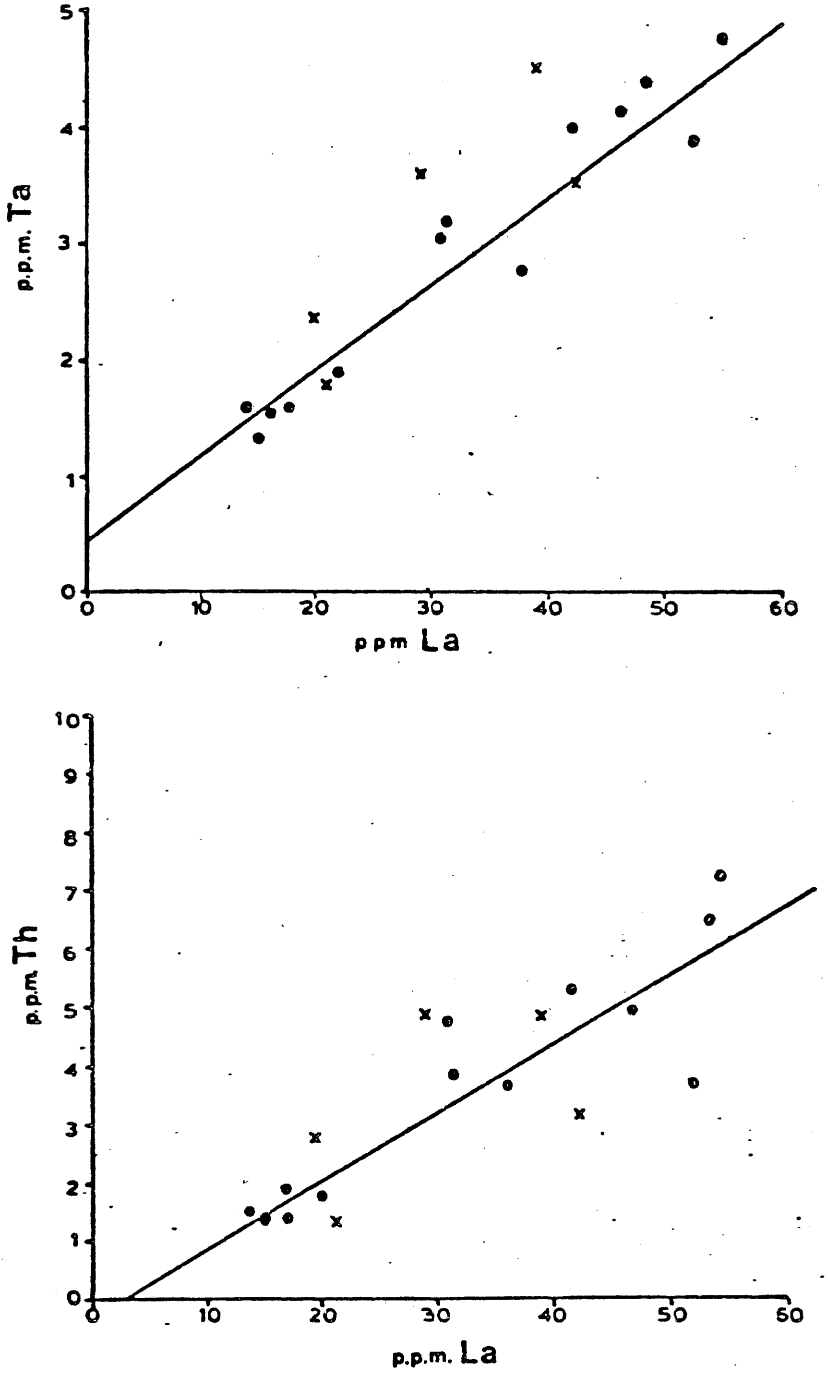


were all mobile, and thus cannot be used to determine the original nature or the tectonic setting of the rocks. The differences in the TiO_2, MnO, and P_2O_5 contents between the Cape St. Mary metabasites are largely insignificant, suggesting that these elements are relatively immobile. The immobility of these elements in altered basaltic rocks has been demonstrated and used in discrimination diagrams by Pearce et al (1975), Floyd and Winchester (1978), and by Ridley et al (1973). The relative immobility of TiO_2, MnO, P_2O_5, plus a suite of trace and rare earth elements was demonstrated by Muecke et al (1979), for the metavolcanics in the Yarmouth area. Thus these elements can be used with some confidence in the determination of the original igneous character of the metabasites at Cape St. Mary. Supportive of the "immobile" nature of P and Ti are the correlation plots of these elements versus La, (figure 3.2). The fairly good linear coherence of the plots suggests that metasomatism and metamorphism did not substantially affect the concentrations of these elements.

The metabasites and the St. Alphonse gabbro are plotted on the TiO_2 - P_2O_5 diagram (figure 3.3) of Ridley et al (1973). The analyses all fall into the field of alkali basalts, a suggestion supported by REE and trace element data. The plots of the rocks analysed on the TiO_2-K_2O-P_2O_5 diagram (figure3.4) of Pearce et al (1975), fall into the field of non-oceanic basalts; however, the mobility of alkalis (Na_2O, K_2O) in the samples must be kept in mind.

Bracketed symbols on the diagram signify the samples in which alkali movement is suspected to have been considerable.

FIGURE 3.2 - Correlation plots of elements considered as "immobile"

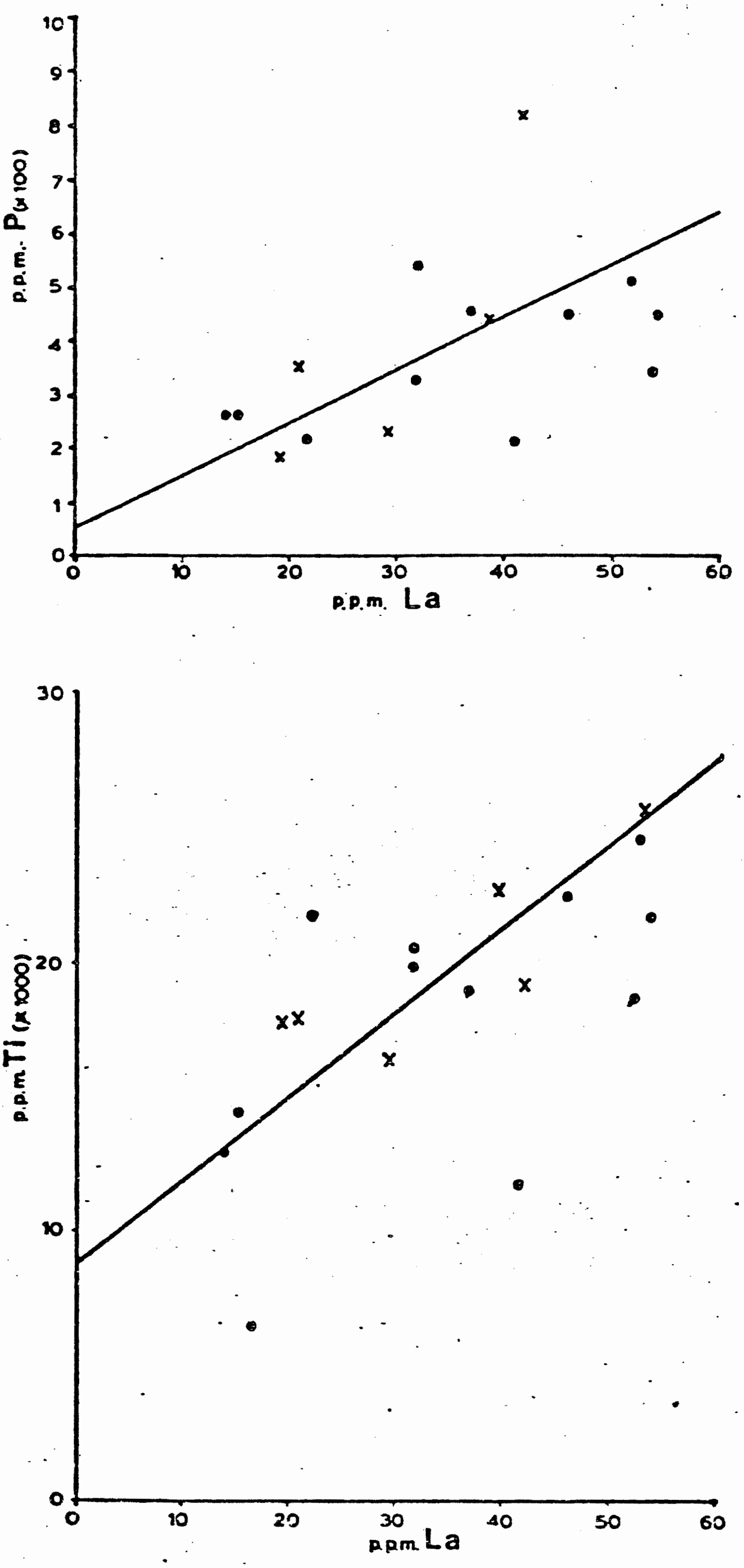


The good linear coherence of these graphs suggests that these elements have been unaffected by metamorphic or metasomatic processes.

x CAPE ST. MARY METABASITES

● YARMOUTH METABASITES

FIGURE 3.2 - Correlation plots of elements considered as "immobile"



FIELDS OF THE TiO_2 - P_2O_5 DIAGRAM:

A: Ocean Ridge Basalts (new crust)

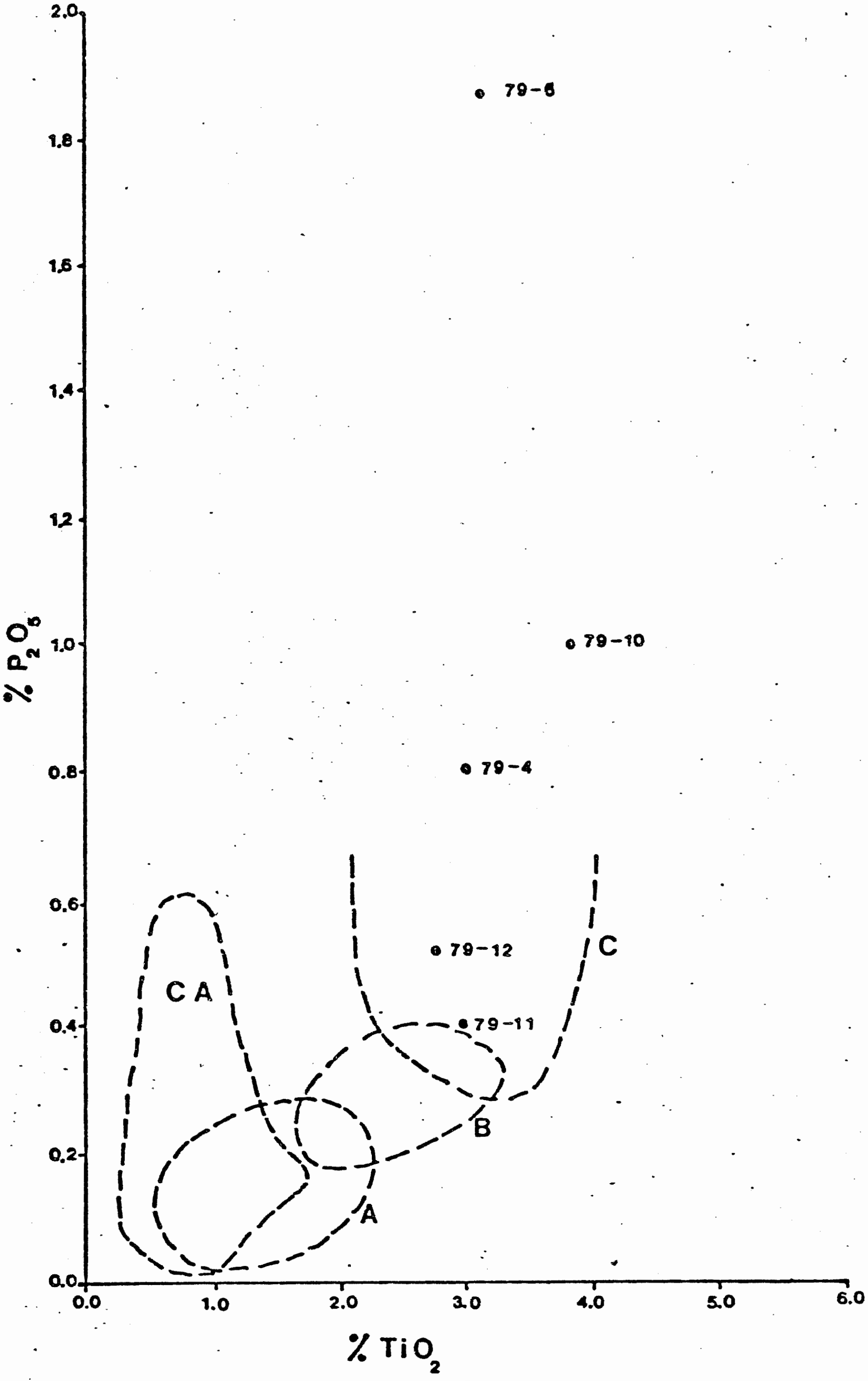
B: Ocean Island Tholeiites

CA: Calc-Alkaline

C: Alkali Basalts

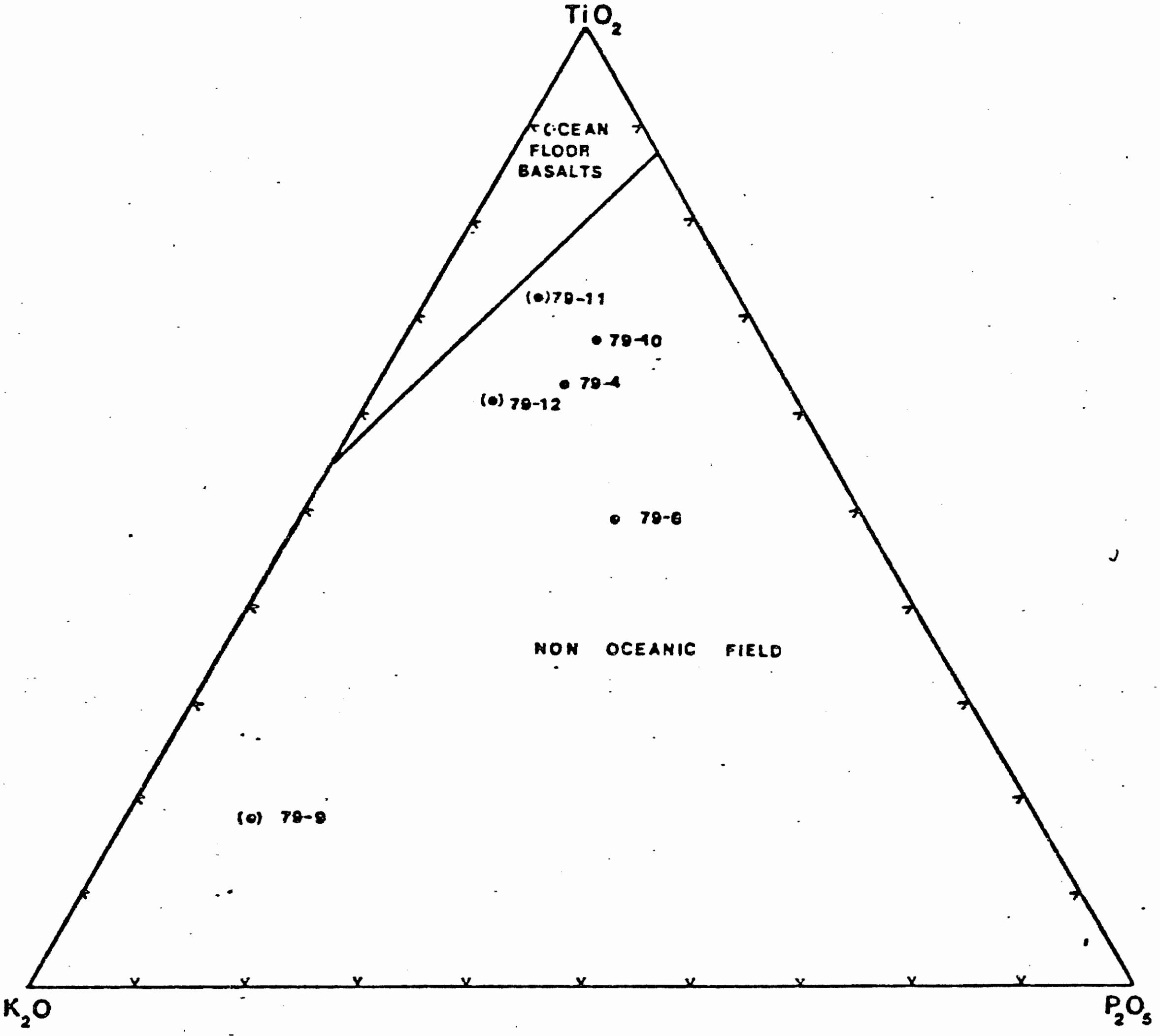
FIGURE 3.3 - TiO_2 - P_2O_5 Discrimination.

Diagram from Ridley *et al* (1973).



FIELDS DEFINED ON FACING PAGE

FIGURE 3.4



TiO_2-K_2O-P_2O_5 DISCRIMINATION DIAGRAM OF PEARCE et al (1975)

Bracketed symbols signify samples in which K_2O mobilization may have been significant.

Normative Compostion

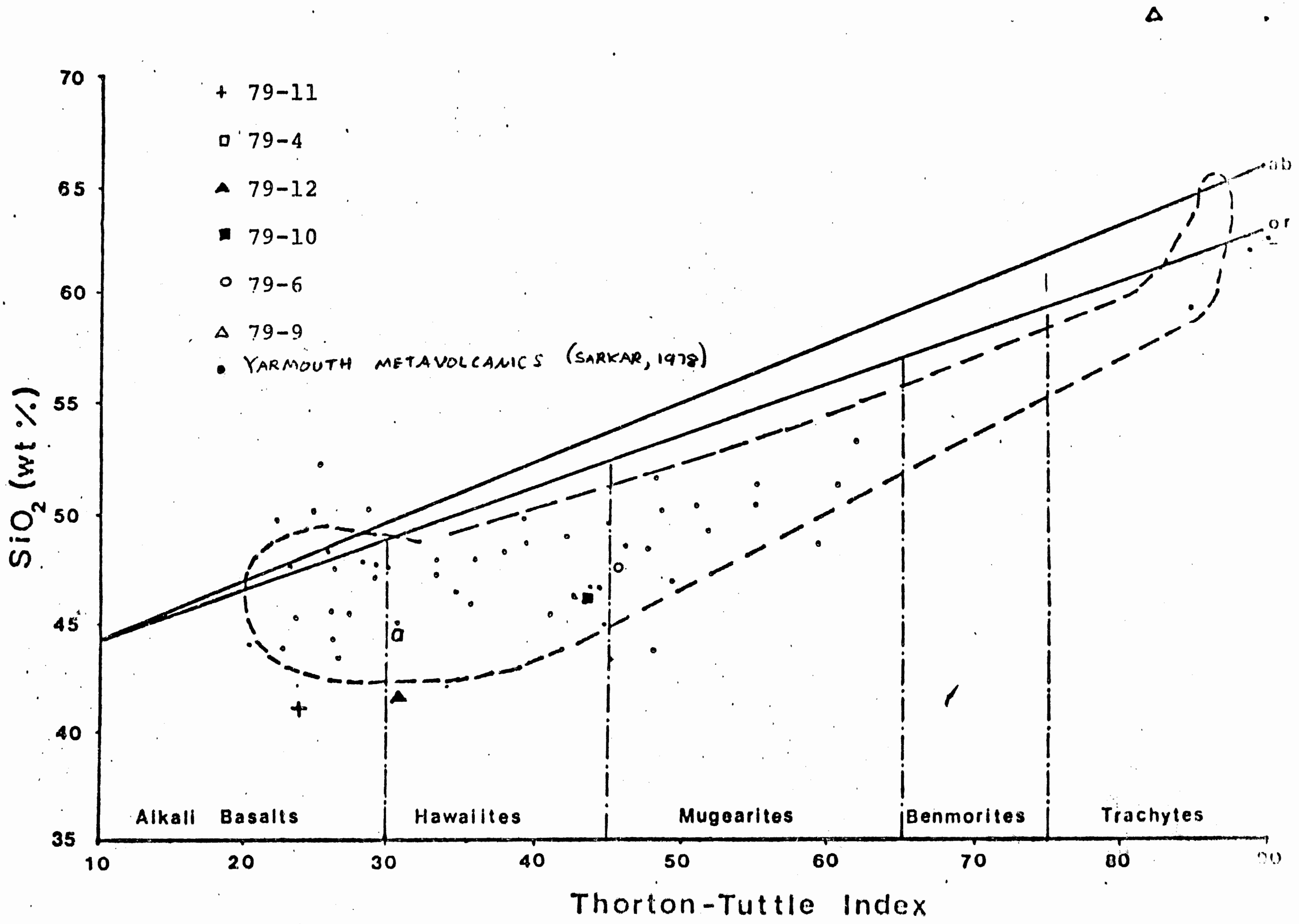
The normative compositions of the St. Alphonse gabbro and the five metavolcanics are seen in table 3.4 The values are computed using the CIPW normative program, with all volatiles and analysed values for FeO and Fe_2O_3 included. Metabasite samples 79-10 and 79-12 contain significant normative corundum indicating that they were subjected to considerable calcium and possibly alkali depletion. Normative corundum of these amounts ~~are~~ is never encountered in unmodified mafic volcanic rocks.

Figure 3.5 is a plot of the Cape St. Mary and Yarmouth metavolcanics on the silica versus differentiation index (D.I.) diagram of Thortun and Tuttle (1960). The D.I. is the sum of the normative percentages of quartz, orthoclase, albite, nepheline, leucite, and kalsilite, and thus serves as a measure of a rocks "basicity". The silica-D.I. diagram is also useful in distinguishing undersaturated from oversaturated rocks. The lines drawn from the silica content of albite and orthoclase at D.I. = 100 to the silica content of anorthite at D.I., divide the diagram into the fields of undersaturated, saturated, and oversaturated rocks.

The metabasites (79-4, 79-10, 79-11, 79-12) and the St. Alphonse gabbro (79-6) all fall in the undersaturated fields of alkali basalts and hawaiites, which is where the majority of the samples analysed by Sarkar (1978) fall.

The trend formed by the plots of the Yarmouth metavolcanics suggest the presence of a major differentiated "Hebridean-Hawaiian" type of alkaline suite, and the plots of the Cape St. Mary metabasites could then represent the more basic members of this trend. The basal metafelsites from the Yarmouth and Cape St. Mary White Rock exposures plot very close to each other in the rhyolite field of the silica-D.I. diagram, again illustrating the distinct nature of these units from the metabasites, and indicating the possible tholeiite-rhyolite differentiation trend responsible for the basal volcanic unit of the White Rock Formation. As with other diagrams using the major element chemistry, the silica-D.I. diagram should be used with caution, due to the major element mobility of the rocks.

FIGURE 3.5 - Silica Versus Differentiation (Thorton-Tuttle) Index. From Thorton and Tuttle (1960).



Conclusion

The major element geochemistry of the metavolcanics and the St. Alphonse gabbro is unreliable in characterizing the rocks, and in determining their paleotectonic setting. This is due to the mobility of the major elements, particularly the alkalis and CaO. However, some of the minor elements, TiO_2, and P_2O_5, are relatively immobile, and can thus be used with some confidence in discrimination diagrams. The two diagrams which use TiO2 and P205 as discriminating elements (Pearce et al (1975), Ridley *et al* (1973) suggest the Cape St. Mary metabasites to be within plate, alkali basalts.

CHAPTER IV - TRACE ELEMENT GEOCHEMISTRY

Introduction

Trace elements such as Ti, Zr, Hf, Sc, Th, Y, Nb, Ta, and Mn can form an apparently "immobile" group of elements, and as such behave similarly during metamorphism and metasomatism (Carmichael, Turner, and Verhoogen, 1974, pg. 71). This is especially true for the rare earth elements (REE's), which can be of great importance in the determination of the chemical evolution of volcanic suites because of their unique behavior and geochemical coherence. The trace elements and REE's may be excluded or incorporated into different minerals with a greater degree of selectivity than major elements, thus analysis of the variation of the trace and rare earth elements in a suite of igneous rocks can place constraints on the nature and composition of the mineral assemblages with which a magma may have previously equilibrated (Cox, Bell, and Pankhurst, p. 332, 1979). However, before these various trace elements can be used in this capacity, it must be demonstrated that they have indeed remained immobile since the rocks were formed.

Mobility of the Trace Elements

Determination of the mobile and immobile elements of the White Rock metavolcanics has been demonstrated by Muecke et al (1979) for the Yarmouth syncline. Examination of metasomatic gradients, such as epidosite lenses, within the Yarmouth metavolcanics has indicated that Na_2O, K_2O, CaO, Fe_2O_3, Fe, MgO, Li, Rb, Sr, Co, and Cs, were mobile during the metasomatism. Thus any discrimination tests conducted using these elements are apt to be erroneous. However, they also demonstrated that the concentrations of TiO_2, P_2O_5, Zr, Hf, Sc, Cr, Th, Y, REE, Nb, Ta, and Mn do not change significantly during metasomatism.

Immobility of trace elements outside of the documented metasomatic gradients has been demonstrated by Muecke et al (1979) using plots of REE versus the elements which have been found to be immobile in the metasomatic zonations. The plots yielded excellent linear correlations, typical of differentiated igneous suites. It is unlikely that such good correlations of diverse elements could have been maintained in the metavolcanics if the elements had undergone redistribution during metamorphism.

These findings of element mobility and immobility in the Yarmouth metavolcanics are not directly applicable to the metavolcanics at Cape St. Mary, as no well-developed metasomatic gradients were encountered, and the rocks were subjected to a lower grade of metamorphism. However, the use of correlation plots of elements considered as "immobile" can be used for the Cape St. Mary metavolcanics. The correlation plots of "immobile" trace elements (figure 3.2) are compiled from the metavolcanics at Yarmouth (Sarkar, 1978), and from the metavolcanics at Cape St. Mary. As is seen for the Yarmouth metavolcanics, the good linear coherence of the plots, especially of La versus Ta and La versus Th, suggests that metamorphism has not substantially affected the concentrations of these elements. The trace elements can therefore be used with greater confidence than the major elements in discrimination diagrams for the Cape St. Mary metavolcanics.

Method

Nine trace elements were analysed by instrumental neutron activation analysis (INAA): Ba, Co, Cr, Cs, Hf, Sc, Ta, Th, U, as well as eight REE: La, Ce, Nd, Sm, Lu, Yb, Tb, Lu. Rock standards BCR-1 and AGV-1 were analysed simultaneously. The trace element results are given in table 4.1, and the REE results are given in table 4.2. The REE abundances were normalized to chondritic values using the values of Frey _et al._, (1968), Table 4.3. The normalized abundances of the samples are plotted in figures 4.3 and 4.4.

TABLE 4.1

TRACE ELEMENT CONCENTRATIONS (ppm)

Element	79-4	79-6	79-9	79-10	79-11	79-12	BCR-1*	AGV-1*
Ba	381	549	130	259	312	663	737 (680)	1115 (1200)
Co	54.0	36.2	79.1	98.8	60.6	56.3	36.5 (37)	14.7 (17)
Cr	202	12.9	7.61	646	650	402	20.8 (16)	10.6 (12)
Cs	1.73	7.82	1.67	1.40	1.34	2.32	1.03 (0.95)	1.30 (1.4)**
Hf	3.95	7.74	5.75	5.17	5.17	6.57	4.83 (4.5)	5.06 (5.2)
Sc	24.9	19.9	1.53	28.1	28.1	21.4	35.2 (34)	12.6 (12)
Ta	1.82	3.53	4.30	2.37	2.37	3.60	0.84 (0.91)**	0.98 (0.9)**
Th	1.37	3.22	20.0	2.08	2.08	4.88	6.78 (6.0)	5.75 (6.4)
U	0.29	0.04	3.26	0.28	0.28	1.18	1.98 (1.8)	1.68 (2.0)

*Accepted values in brackets, from Abbey (1977)

**Accepted values from Flanagan (1976)

TABLE 4.2

RARE EARTH ELEMENT CONCENTRATIONS (ppm)

Element	79-4	79-6	79-9	79-10	79-11	79-12	BCR-1*	AGV-1*
La	21.2	42.0	23.7	39.2	19.5	29.3	24.8 (25)	36.8 (45)
Ce	48.7	102.0	49.1	89.3	44.3	66.8	52.1 (54)	65.2 (63)
Nd	33.1	69.1	19.8	49.9	28.3	36.2	31.5 (29)	36.1 (39)
Sm	6.86	13.5	3.94	9.11	5.79	6.80	6.73 (6.6)	5.79 (5.9)
Eu	2.75	5.30	0.44	3.10	1.87	2.28	2.00 (1.9)	1.65 (1.7)
Tb	1.05	1.95	0.64	1.56	0.78	0.97	1.13 (1.0)	0.63 (0.7)
Yb	1.76	3.27	1.84	1.34	1.48	1.70	3.24 (3.8)	1.76 (2.0)
Lu	0.32	0.60	0.28	0.21	0.29	0.29	0.57 (0.6)	0.27 (0.3)
TOTAL	115.74	237.72	99.74	193.72	102.31	144.34		
Eu*	32.7	63.5	19.0	41.7	26.9	31.9		
Eu/Eu*	1.22	1.21	0.34	1.08	1.01	1.04		

*ACCEPTED VALUES IN BRACKETS, FROM ABBEY (1977)

TABLE 4.3

COMPOSITE OF NINE CHRONDITE VALUES* (ppm)

La	0.330 ± .013
Ce	0.88 ± .01
Nd	0.60 ± .01
Sm	0.181 ± .006
Eu	0.069 ± .006
Tb	0.047 ± .001
Yb	0.200 ± .007
La	0.034 ± .002

*VALUES ARE FROM FREY ET AL. (1968).

FIGURE 4.3 - REE patterns of the four Cape St. Mary Metabasites and the St. Alphonse Gabbro.

Areas between the dashed lines: Alkali, basalts, and the intermediate rocks of rift related volcanism, Barbieri *et al.*, (1975).

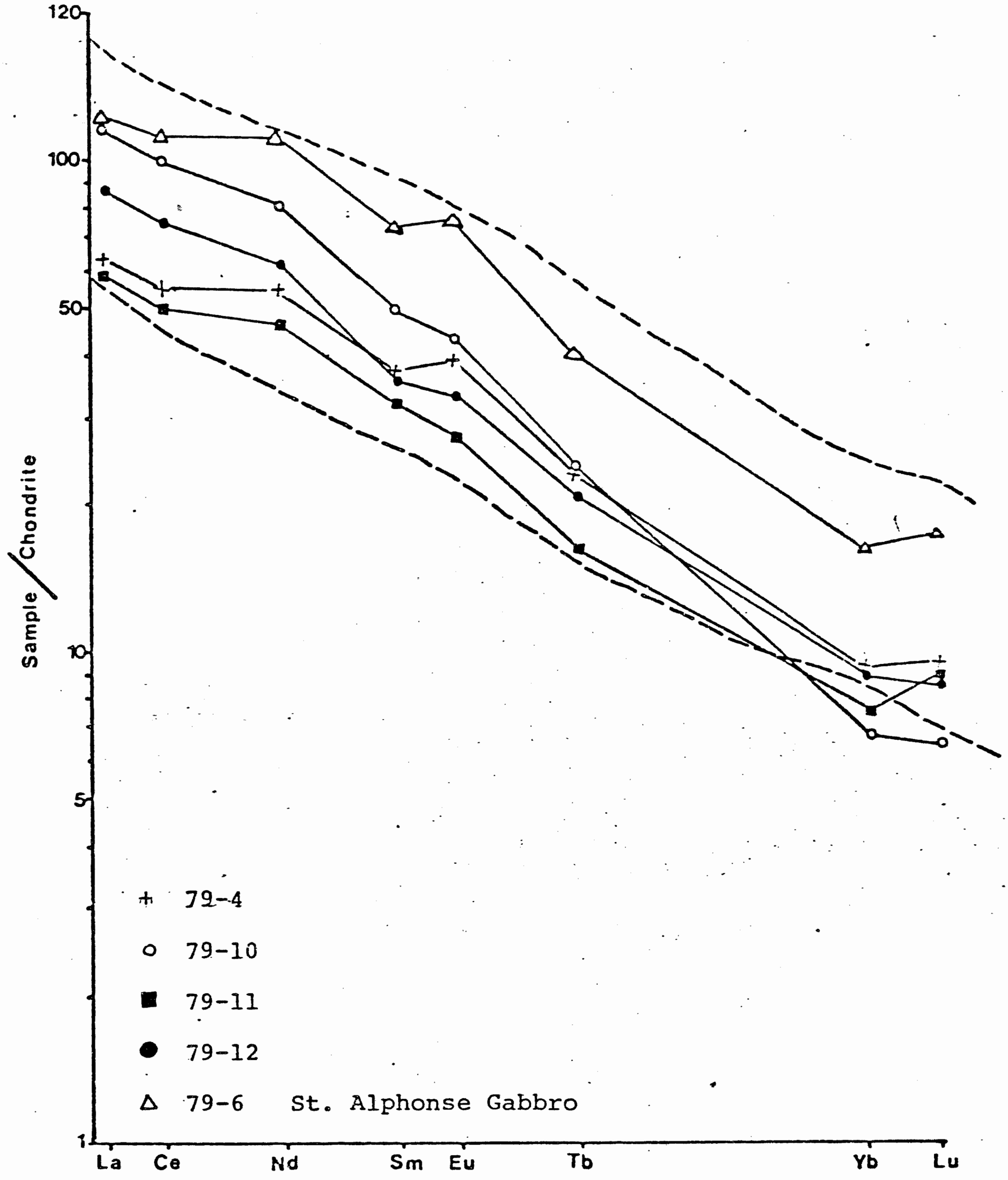


FIGURE 4.4 - REE pattern of the the basal metafelsite unit (79-9) from Cape St. Mary compared to the REE patterns of the basal metafelsite from the Yarmouth syncline (Sarkar, 1978), and to a fresh comendite (Ewart <u>et</u> <u>al</u>, 1968).

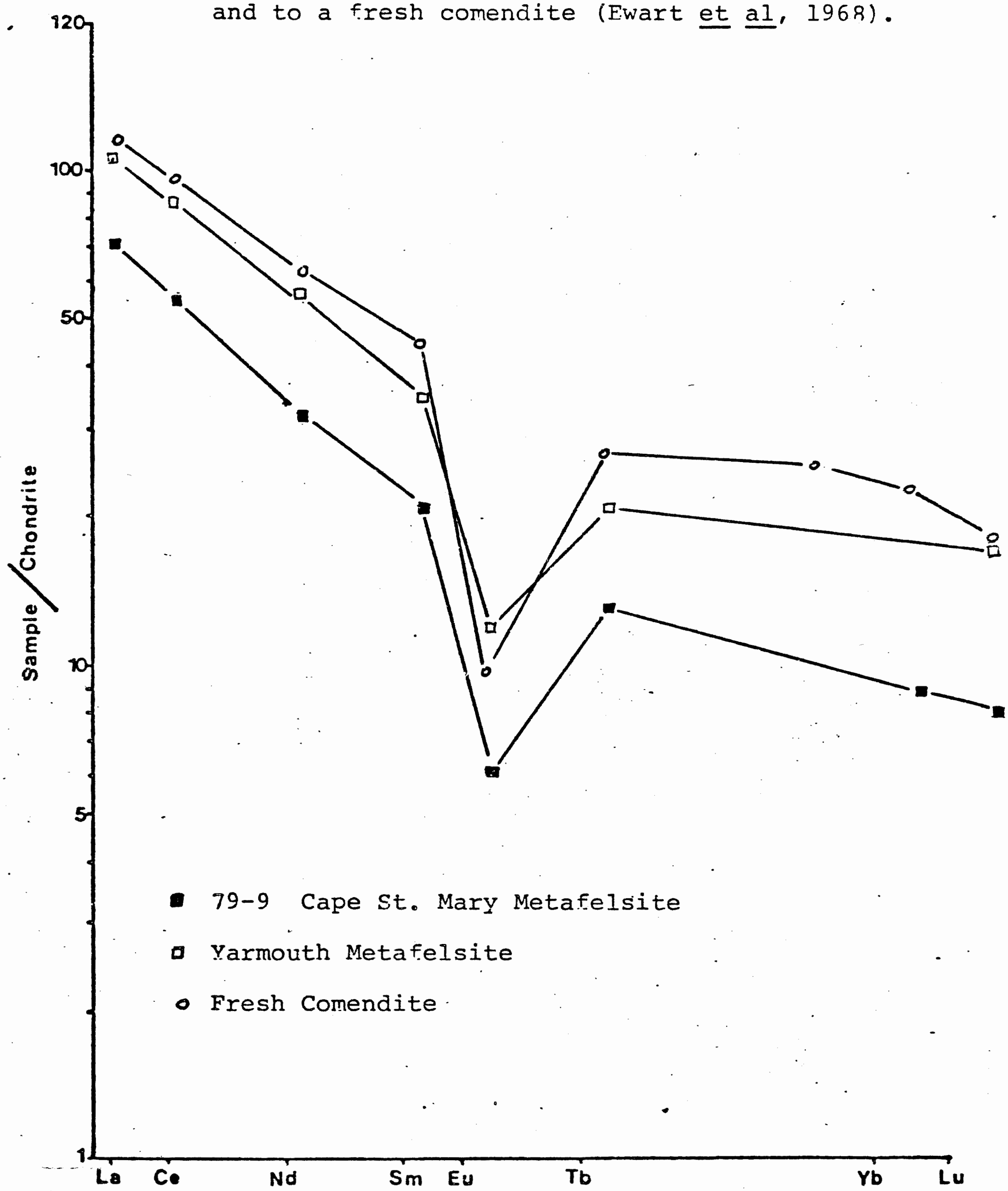
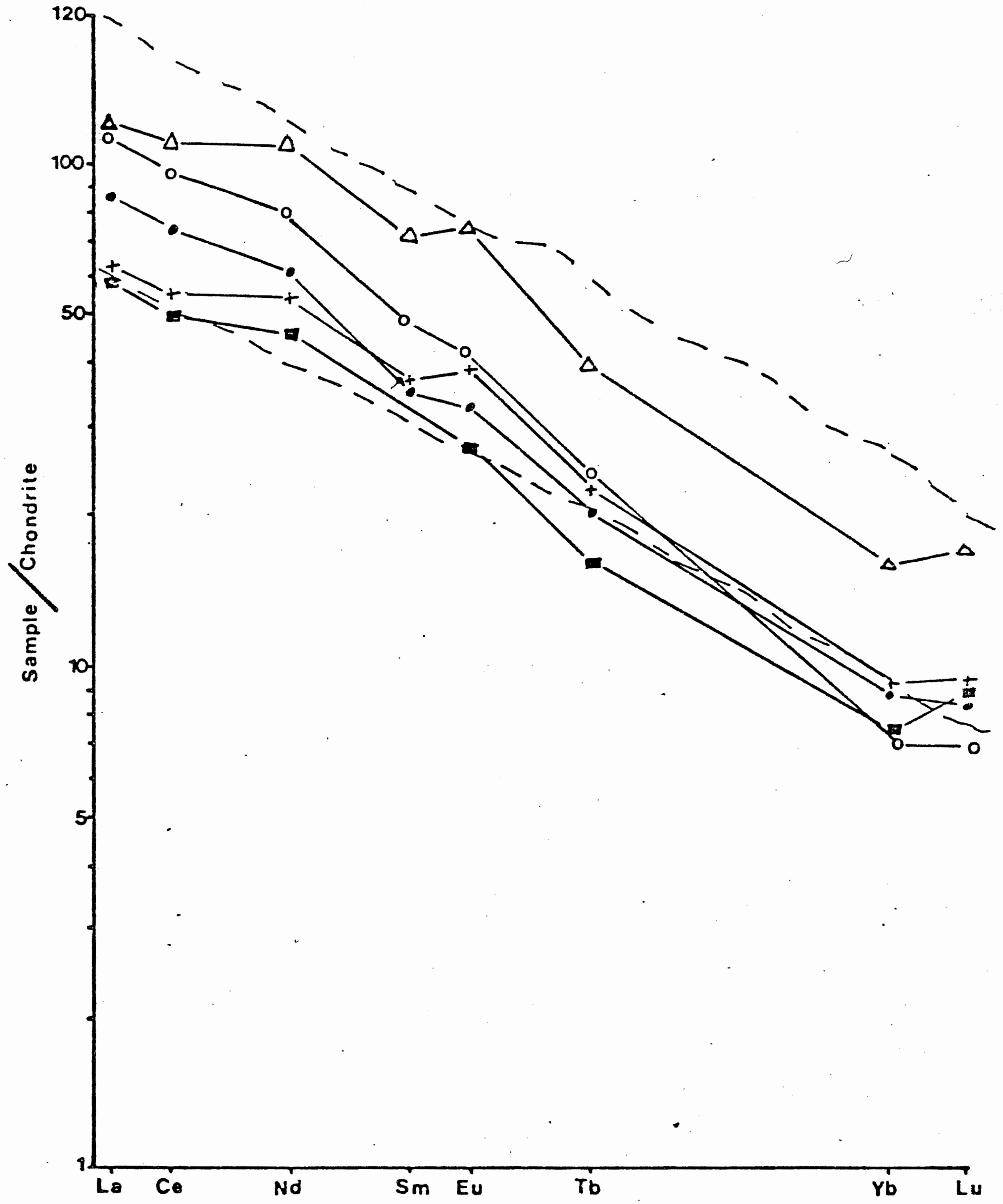


FIGURE 4.5 - Comparison of the four Cape St. Mary metabasite patterns with the field of the Yarmouth metabasites (bounded with dashed lines) (Sarkar, 1978).

Symbols same as in Figure 4.3.



THE RARE EARTH ELEMENTS

The plots of the four metabasite units (figure 4.3) are all very similar to each other, strongly suggesting a close genetic interrelationship. The patterns all show a straight line pattern showing a strong enrichment of the light REE (LREE), with a linear decrease in REE concentrations with increasing element atomic weight. Also noticeable in the patterns are the slight positive europium anomalies, and the limited variation in absolute amounts of the total REE concentrations of the four units. These pattern characteristics are identical to those of typical alkali basalts (e.g., Gast,1968, Kay and Gast, 1973, Barbieri _et al._, 1975), and to those of the Yarmouth metabasites, which Sarkar (1978) identified as largely comprised of alkali basalts on the basis of their REE patterns (figure 4.5).

The straight, linearly decreasing alkali basalt patterns displayed by the Cape St. Mary metabasites provide additional evidence that their REE contents may have remained unaffected by any metamorphic or weathering processes. Such processes have been found to often result in differential LREE enrichment (e.g., Frey _et al._, 1974, Ludden and Thompson, 1978), which would be evident as a "bent" REE pattern.

The slight positive europium anomalies observed in the Cape St. Mary metabasites are defined by the ratio of the observed chondrite normalized europium value to the value obtained by a straight line extrapolation between Sm and Tb values. This ratio, designated as Eu/Eu* is greater than one if there is a relative europium enrichment, and less than one if there is a relative europium depletion. A comparison of Eu/Eu* with the total REE content is seen in figure 4.6 and table 4.2.

The Eu/Eu* values remain fairly constant with increasing REE contents for the metabasite units A, B, and C (79-10, 79-11, 79-12). The Eu/Eu* value for the upper most metabasite unit, unit D (79-4) is higher than the values for the other 3 metabasites, and is almost identical to the Eu/Eu* value for the St. Alphonse gabbro (79-6). The higher Eu/Eu* values for these two units suggests that they may be slightly more evolved than the other units.

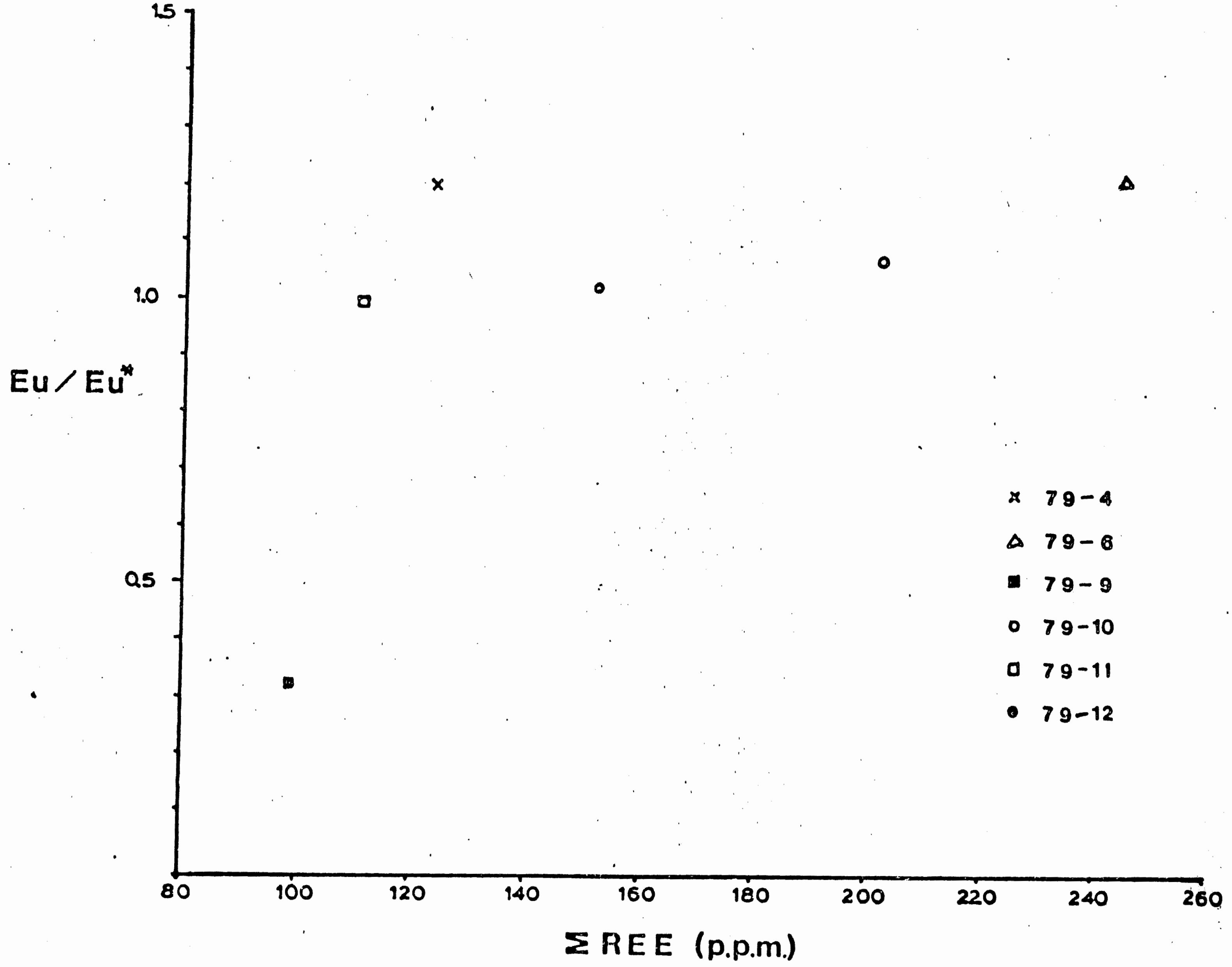
These anomalies can be explained in several ways. Prominent positive europium anomalies are found in the REE distribution patterns for feldspars, which indicates that Eu^{2+} is incorporated preferentially into the crystalline plagioclase phase by substitution of Ca^{2+}. Enrichment in feldspar phenocrysts in the metabasites and the St. Alphonse gabbro relative to the parental magma could explain the positive europium anomalies. However, albitization has destroyed all or most of the plagioclase in the metabasites, and no excessive plagioclase enrichment is noted in the gabbro.

Positive europium anomalies have been seen in many gabbros (e.g., Towell, et al., 1965, Frey et al., 1968, Dostal and Muecke, 1978). Dostal and Muecke attribute positive europium values seen in mid-ocean ridge gabbros to accumulation of plagioclase. This explanation could be applicable to the St. Alphonse gabbro, as plagioclase is encountered as a cumulate phase. Leeman (1976) maintains that small positive europium anomalies found in some basic rocks are more probably features resulting from exclusion of Eu^{2+} by residual clinopyroxene in the source region. Sarkar (1978) also noted a positive europium anomaly in metabasite sample C-7/74 from the Yarmouth syncline, which he attributes to the crystallization and accumulation of plagioclase in the residual magma.

Another notable feature is the high total REE content, but similar REE pattern, of the St. Alphonse gabbro to the metabasites. The REE pattern and the petrography of the gabbro show it to be alkalic and, therefore, probably chemically related to the metabasites. This relationship is reinforced by the suspected pre-deformational age of the intrusion (see Chapter 2) which suggests that the gabbro is either the intrusive equivalent of the metavolcanics or possibly a feeder pipe. If the gabbro was one of the feeders of the volcanics, the total REE content should be less than that of the volcanics, as the REE are partitioned preferentially into the melt. Thus the gabbro probably does not represent a feeder pipe for the metabasites exposed at Cape St. Mary.

This does not, however, rule out the possibility that the gabbro represents the feeder pipe for slightly more evolved rocks which probably occurred above the exposed rocks at Cape St. Mary. Several lines of evidence support this. On the basis of lithology and stratigraphic positioning,

FIGURE 4.6 - Eu/Eu* versus total REE content diagram for the Cape St. Mary Metavolcanics and the St. Alphonse Gabbro



Lane (1980) demonstrated the Cape St. Mary White Rock exposures as corralable with the lowermost parts of the formation occurring in the Yarmouth syncline. The lower metavolcanic units at Yarmouth have been shown to be the metamorphosed equivalents of alkali basalts, which gradually become more evolved higher up in the stratigraphic column (Sarkar, 1978). Thus, the lower parts of the White Rock Formation probably represent the earliest, least differential products of alkali volcanism, which ~~is~~ are followed by increasingly differentiated rocks. The silica-D.I. diagram (figure 3.5) shows the strongly differentiated volcanic suite of the Yarmouth syncline, and the very basic, less differentiated Cape St. Mary metavolcanics. The diagram also illustrates the more evolved nature of the St. Alphonse gabbro from the Cape St. Mary metabasites. These lines of evidence then indicate that the St. Alphonse gabbro was probably a feeder for the more evolved and stratigraphically higher metavolcanics which once occurred at Cape St. Mary, and which are still preserved in the Yarmouth syncline.

The REE pattern for the metafelsite shows the total REE content and strong europium deficiency typical of strongly fractionated acid rock types. Figure 4.4 shows that the REE pattern of the Cape St. Mary metafelsite is very similar to the basal metafelsite of the Yarmouth syncline, although absolute abundances are somewhat different. Also shown is the typical REE pattern of a fresh comendite, which again is very similar to that of the Cape St. Mary meta-felsite.

OTHER TRACE ELEMENTS

The trace element contents of the analysed rocks are given in table 4.1. Figure 4.7 is a plot of the White Rock metavolcanics from both Yarmouth (Sarkar, 1978) and Cape St. Mary on the revised Th-Hf-Ta tectonic discrimination diagram of Wood (1980). This diagram assumes that:

1. The element concentrations of the rocks reflect those of the original magmas (i.e., excluding cumulates, etc.).

2. The Th, Hf, and Ta concentrations of the rocks have not changed since their formation.

The fields of the different tectonic environments are defined as:

A) Normal type and mid-ocean ridge basalts (N-type MORB).

B) Enriched type mid-ocean ridge basalts (E-type MORB).

C) Alkaline within plate basalts and differentiates.

D) Destructive plate-margin basalts and differentiates.

The plots of the four Cape St. Mary metabasalts all fall within a fairly tight group, reinforcing the REE data which suggests the metabasalts to be of alkalic affinity. The St. Alphonse gabbro is included in the diagram to illustrate the chemical similarities between the gabbro and the metabasalts. This suggests the immobile nature of the trace elements in the gabbro and the metabasites, despite different degrees of alteration in these units. The metabasites from Yarmouth analysed by Sarkar (1978) fall mainly in the field bounded by dashed lines surrounding the B-C boundary line, and is taken to represent an area of possible overlap between the two fields. The boundaries of the overlap area are drawn by Wood (1980) from plots of alkalic basalts evidently somewhat contaminated by a crustal component. Wood (1980) points out that very few of the analysed lavas of his study actually plot between the dashed lines, but those that do cannot be classified with great certainty using the diagram.

Also included in the Th-Hf-Ta diagram are the plots of the metafelsite from Cape St. Mary (79-9), and the total metafelsite (S-2/74) from the Yarmouth syncline (Sarkar, 1978). These two units plot near the calc-alkaline side of field D, the field of destructive plate-margin basalts and differentiates. This would indicate that the magmas of the two metafelsites ha~~s~~ve undergone a strong degree of crystal fractionation, which tends to push the residual liquid towards the Th apex of the triangle, as Hf and Ta are incorporated preferentially to Th into Fe-Ti oxides, clinopyroxenes, and other minor phases (Wood et al., 1979). The similar stratigraphic positioning of these two basal metafelsites and their trace elements similarity as seen in the Th-Hf-Ta diagram indicate the possibility of using trace element geochemistry to correlate metavolcanic units in the various stratigraphic sections of the White Rock Formation.

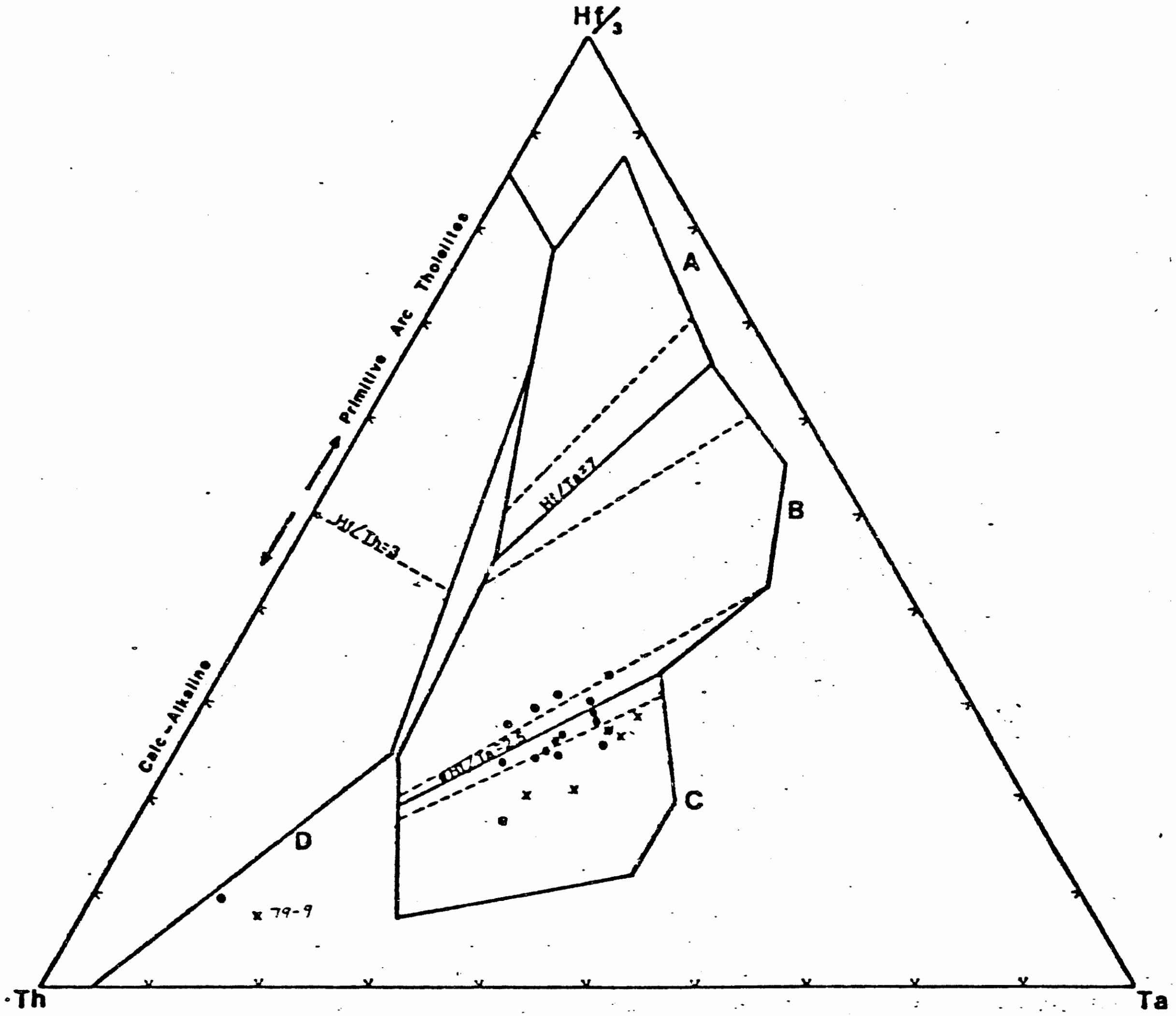
FIGURE 4.7

Th-Hf-Ta diagram. Modified version of WOOD (1980) is shown. Dashed lines on either sides of a solid line indicate areas of possible overlap between the two fields.

* Cape St. Mary Metavolcanics

■ St. Alphonse Gabbro

● Yarmouth Metavolcanics



The fields are defined as follows:

A. Normal type mid-ocean ridge basalts (N-type MORB)
B. Enriched type mid-ocean ridge basalts (E-type MORB)
C. Alkaline within plate basalts and differentiates
D. Destructive plate-margin basalts and differentiates

CONCLUSIONS

The correlation plots using elements considered to be "immobile" yield good linear coherences, indicating that these trace elements probably remained relatively immobile during the metasomatism and metamorphism of the White Rock Formation at Cape St. Mary. Immobility of the REE at Cape St. Mary is also supported by the straight, linear decreasing patterns of the metabasites which show that there was no differential LREE enrichment. These observations are supported by the conclusions of a trace element study of metasomatic gradients and correlation plots from the Yarmouth metavolcanics by Muecke _et_ _al_., (1979).

Demonstration of trace element immobility in the Cape St. Mary metavolcanics enables these elements to be used with confidence as geochemical discriminators for the metavolcanics. The metabasite REE patterns show the metabasites to be closely related to each other, and shows them to be the metamorphic equivalents of alkali basalts. The metafelsite REE pattern shows the unit to be of rhyolitic affinities, and probably geochemically related to the basal metafelsite occurring in the Yarmouth syncline. These conclusions are supported by the Th-Hf-Ta diagram of Wood (1980), which shows the metabasites and the St. Alphonse gabbro to be alkalic within-plate basalts and differentiates. The diagram also illustrates the trace elements similarity of the Cape St. Mary metafelsite and the Yarmouth metafelsite. It is therefore possible to correlate this basal metafelsite unit of the White Rock Formation by its trace element geochemistry.

The REE patterns of the St. Alphonse gabbro show it to be closely related to the Cape St. Mary metabasites, but somewhat more evolved. This raises the possibility that the gabbro is not a feeder for any metavolcanics observed at Cape St. Mary, but may be the feeder for more evolved volcanics, which, on the basis of stratigraphic correlations with the Yarmouth syncline probably once occurred stratigraphically above the Cape St. Mary metavolcanics.

REE patterns found in the Yarmouth metabasites and metafelsite by Sarkar (1978) led to the suggestion that the White Rock volcanics are the result of two different magmas, the basal metarhyolites evolving from a basaltic magma of tholeiitic-rhyolite affinities, and the metabasites and metatrachyte evolving from a basaltic magma of alkali basalt-mugearite-benmorite-trachyte affinities. As the REE patterns of the basal metafelsite and the metabasites from the White Rock at Cape St. Mary are very similar to the REE patterns from the Yarmouth rocks, this conclusion of Sarkar (1978) appears to be also applicable to the White Rock at Cape St. Mary.

CHAPTER V - PYROXENE CHEMISTRY

Introduction

The relict clinopyroxenes of unit D in the White Rock Formation at Cape St. Mary are the first recorded occurrence of primary mafic minerals in the White Rock metavolcanics. This is of some significance as previous petrologic investigations (e.g., Sarkar, 1978) are based entirely upon secondary minerals produced by extensive alteration and higher metamorphic grades. The pyroxenes may be used as an independent petrologic, geochemical, and paleotectonic interpretation~~s~~ of the White Rock Formation. Pyroxene chemistry may be used to help identify parental magma type, and paleotectonic environment.

Nisbet and Pearce (1977) have suggested that clinopyroxene~~s~~ chemistry can be used as a discriminator for basalts. However, the useful~~l~~ness of a clinopyroxene chemistry discriminator has been questioned by Wark and Clarke (1980). They identified the paleotectonic environment of the North Mountain basalts which occur along the south coast of the Bay of Fundy by the use of REE and trace element techniques. The paleotectonic environment suggested by the use of clinopyroxene compositions as a discriminator was in conflict with that suggested by the more reliable REE and trace element discriminators. Wark and Clarke (1980) therefore only place a moderate degree of confidence in the use of clinopyroxene as a discriminating technique.

Methods

Fifteen clinopyroxene grains from the St. Alphonse gabbro and fourteen pyroxene phenocrysts from unit D at Cape St. Mary were analysed by the electron microprobe at Dalhousie University. Precision data for the analyses are given in the Appendix.

Where possible, the centres of grains, a point between the centre and the rim, and the rims were analysed. All plots of the clinopyroxenes are of either the grain centre, or an average of the grain centre and the "mid" point. Although the clinopyroxenes in both the gabbro and unit D were found to be unzoned, rim analyses are not used in any diagrams or calculations as the grain rims would be the most susceptible part of a grain to alteration.

Discussion

The microprobe analyses reveal the pyroxenes in both units to be "augitic", although they have some significant compositional differences. The augites in unit D are slightly more diopsidic than the augites of the St. Alphonse gabbro, with significantly more MgO and less FeO. Compositional differences between the pyroxenes in the two rock units are seen in the pyroxene element variation diagrams, figures 5.2 and 5.3. Averages of the major element compositions of the pyroxenes from the two units appear in table 5.1. Individual pyroxene compositions are plotted on the pyroxene

TABLE 5.1 - Statistical Comparison* of the Major Element Compositions of Pyroxenes from Metabasite Unit D and the St. Alphonse Gabbro to Within-Plate Alkali (WPA) Basalt Pyroxenes of Nisbet and Pearce (1977)

	METABASITE UNIT D			ST. ALPHONSE GABBRO			WPA	
			CONFIDENCE INTERVAL			CONFIDENCE INTERVAL		
	$\overline{X}$	S	AT 95% CONFIDENCE	$\overline{X}$	S	AT 95% CONFIDENCE	$\overline{X}$	S
SiO_2	50.46	0.68	48.99 - 51.93	49.57	0.44	48.62 - 50.52	49.20	2.40
TiO_2	1.37	0.33	0.66 - 2.08	1.28	0.31	0.61 - 1.95	1.77	1.20
Al_2O_3	1.79	0.50	0.71 - 2.87	1.54	0.45	0.57 - 2.51	4.10	2.70
FeO	11.37	0.57	10.41 - 12.60	14.78	0.74	12.99 - 16.19	11.30	5.50
MnO	0.26	0.10	0.04 - 0.48	0.37	0.15	0.05 - 0.69	0.43	0.38
MgO	13.52	0.38	12.70 - 14.34	11.40	0.08	11.23 - 11.57	10.90	3.80
CaO	21.02	0.31	20.35 - 21.69	20.78	0.29	20.15 - 21.41	20.50	2.80
Na_2O	0.00	0.00		0.00	0.00		1.17	1.26
Wo	43.20	0.49	42.14 - 44.26	43.88	0.39	43.02 - 44.72		
En	38.70	0.93	36.69 - 40.71	33.48	3.10	26.78 - 40.18		
Fs	18.10	0.91	16.13 - 20.07	22.64	1.96	18.41 - 26.87		

* STATISTICS on the pyroxenes from the metabasite and the gabbro are based on 14 analyses each.

WPA pyroxene statistics based on 82 analyses.

FIGURE 5.1 - Compositions of pyroxenes from the metabasite (unit D) and the St. Alphonse gabbro plotted on the pyroxene quadrilateral diagram.

Pyroxenes from the metabasite unit D are enclosed by a solid line.

Pyroxenes from the St. Alphonse gabbro are enclosed by a dashed line.

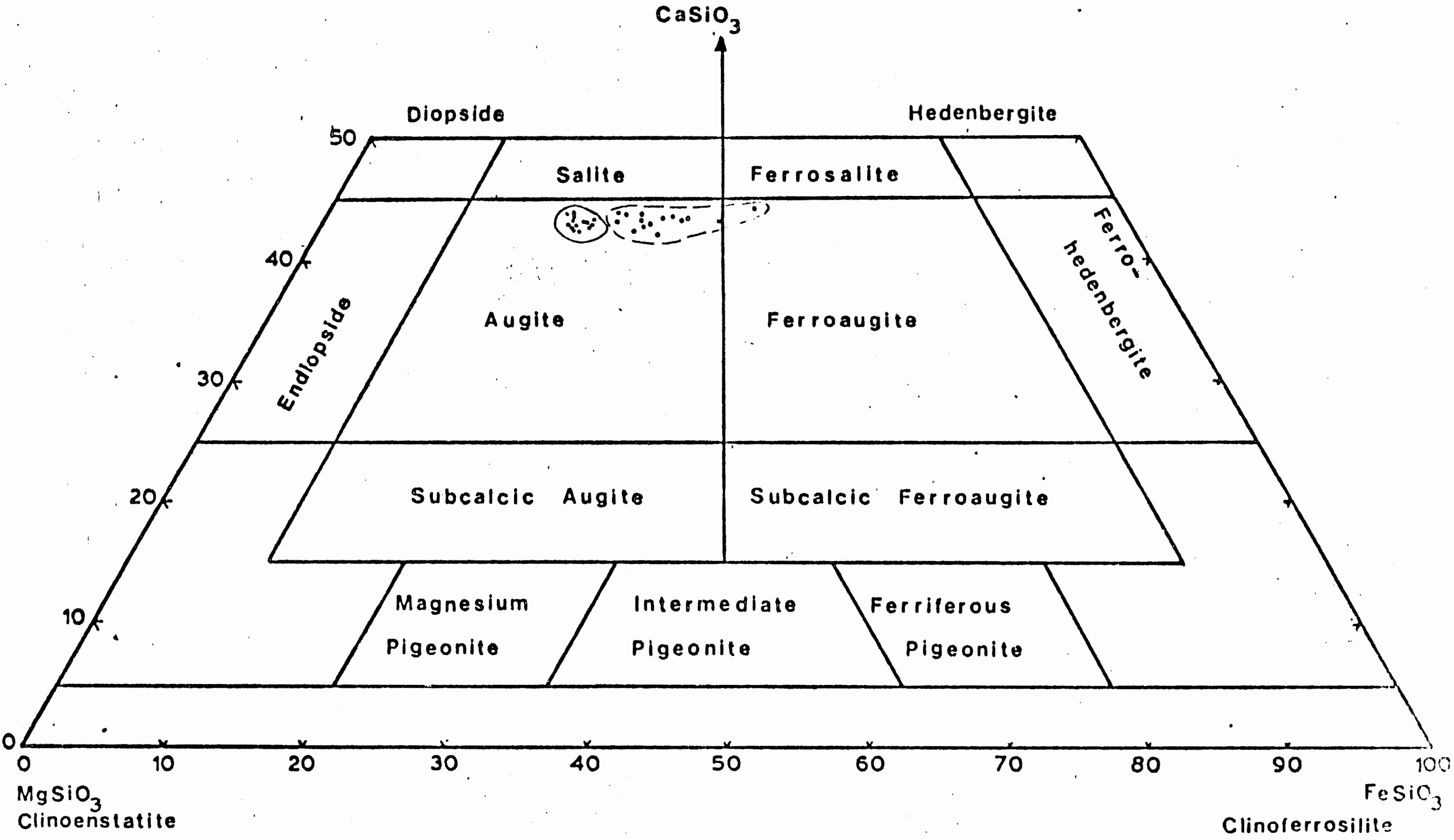
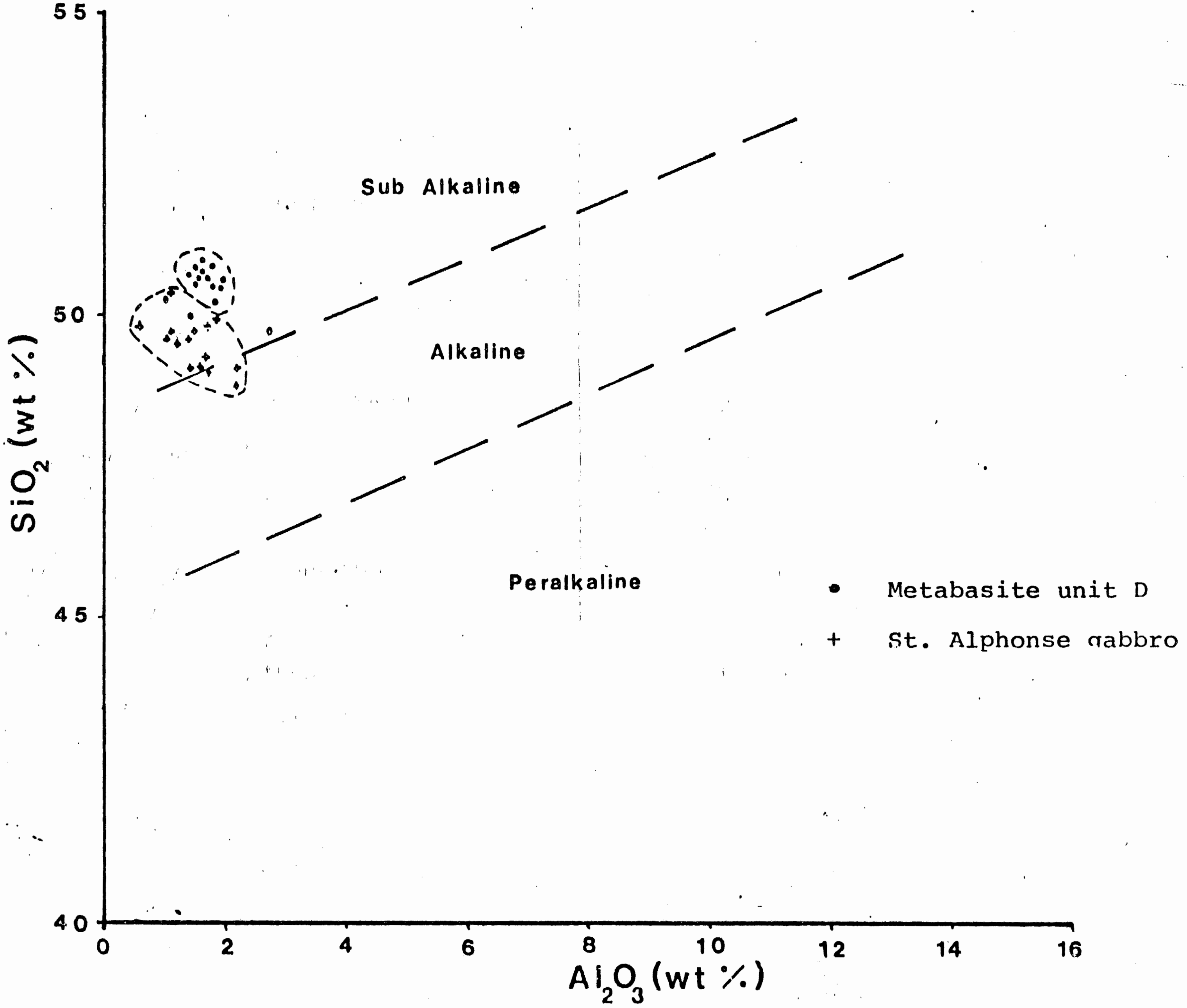


FIGURE 5.2 - Pyroxene compositions from the metabasite (unit D) and the St. Alphonse gabbro plotted on a SiO_2 versus Al_2O_3 diagram, with the fields of LaBas (1962) included.



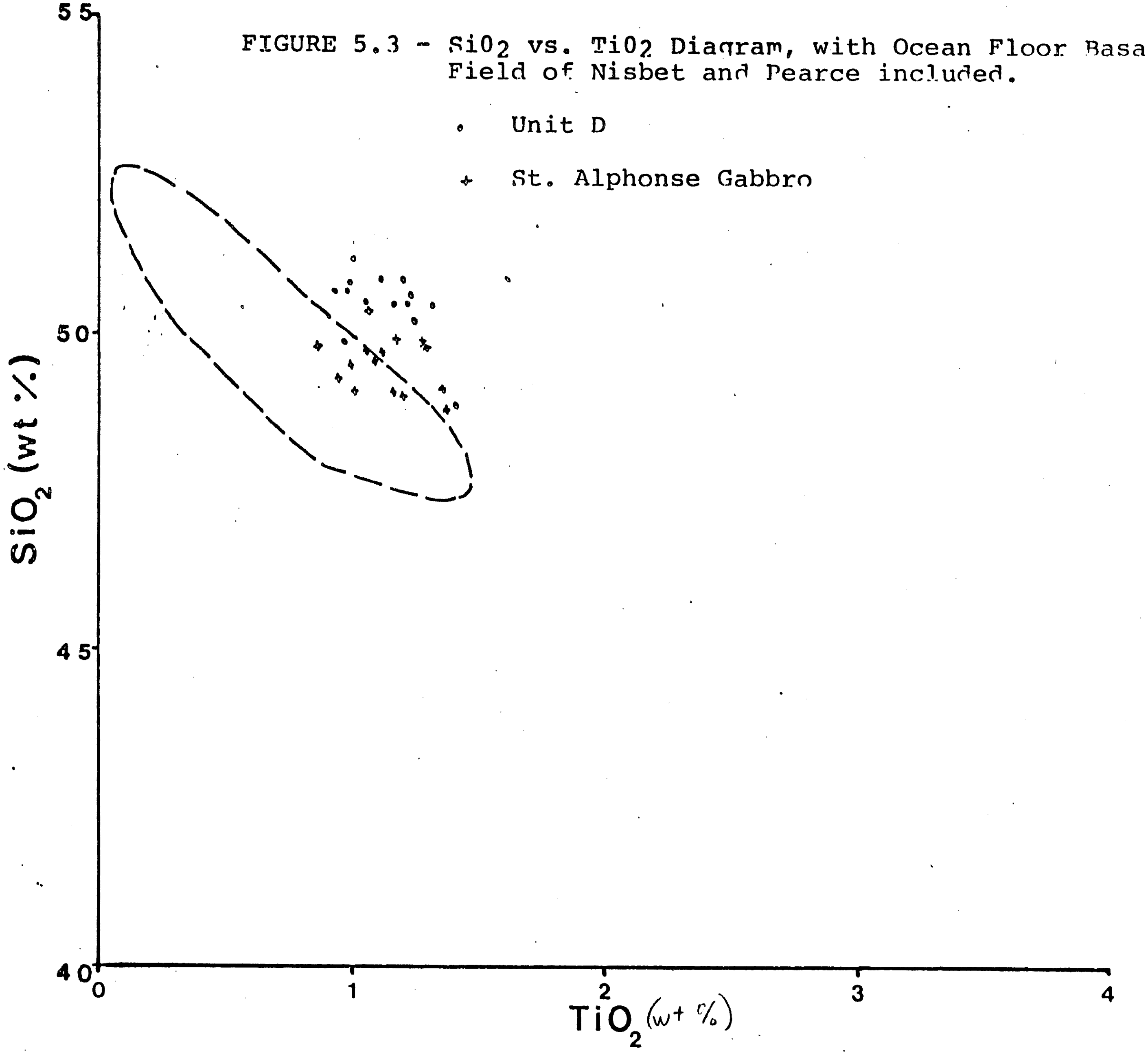


FIGURE 5.3 - SiO_2 vs. TiO_2 Diagram, with Ocean Floor Basalt (OFB) Field of Nisbet and Pearce included.

compositions are plotted on the pyroxene quadrilateral diagram, figure 5.1.

The pyroxene quadrilateral diagram illustrates a very small compositional range of the clinopyroxenes from unit D, and a linear variation in composition of the clinopyroxenes from the gabbro along a calcic augite-calcic ferroaugite line. The line produced by this compositional variation can be continued to intersect the composition of the clinopyroxenes from unit D, thus a possible trend of clinopyroxene crystallization can be roughly defined. Figure 5.4 illustrates several well established clinopyroxene crystallization trends of different rock suites. Gibb (1973) recognized three main types of clinopyroxene crystallization trends for basic magmas:

(i) the augite - ferroaugite trend typical of differentiated intrusions, e.g., Skaergaard and Bushveld intrusions;

(ii) the calcic augite-calcic ferroaugite-hedenbergite trend of mildly alkaline basic magmas, e.g. Shiant Isles sill (Gibb, 1973), and Japanese alkali basalts (Aoki, 1964);

(iii) the salite-ferrosalite-aegirine trend of strongly alkaline basic rocks, e.g., the Shonkin Sag laccolith (Nash and Wilkinson, 1970, <u>in</u> Larson, 1976).

The line defined by the pyroxenes analysed from unit D and from the gabbro is very close to the trends formed by the mildly alkaline types of clinopyroxene crystallization. It must be emphasized that the trend of the clinopyroxenes from unit D and from the gabbro is very rough, and based upon far fewer analyses than the other trends shown in figure 5.4.

Other clinopyroxenes compositional characteristics that have been used to identify the magma type of the host lava are the amounts of SiO_2 and Al_2O_3 (LeBas, 1962). The clinopyroxenes from the St. Alphonse gabbro and metabasite unit D from Cape St. Mary fall into the subalkaline field of the diagram (figure 5.2), suggesting the host magmas were subalkaline in nature. This suggestion is in conflict with conclusions based on the clinopyroxene crystallization trend and on the alkalic nature of the basalts that was determined by the more reliable REE and trace element data.

Nisbet and Pearce (1977) produced a magma-type discrimination diagram utilizing the major element chemistry of the clinopyroxene grains. The relevant discriminant functions are F_1 and F_2;

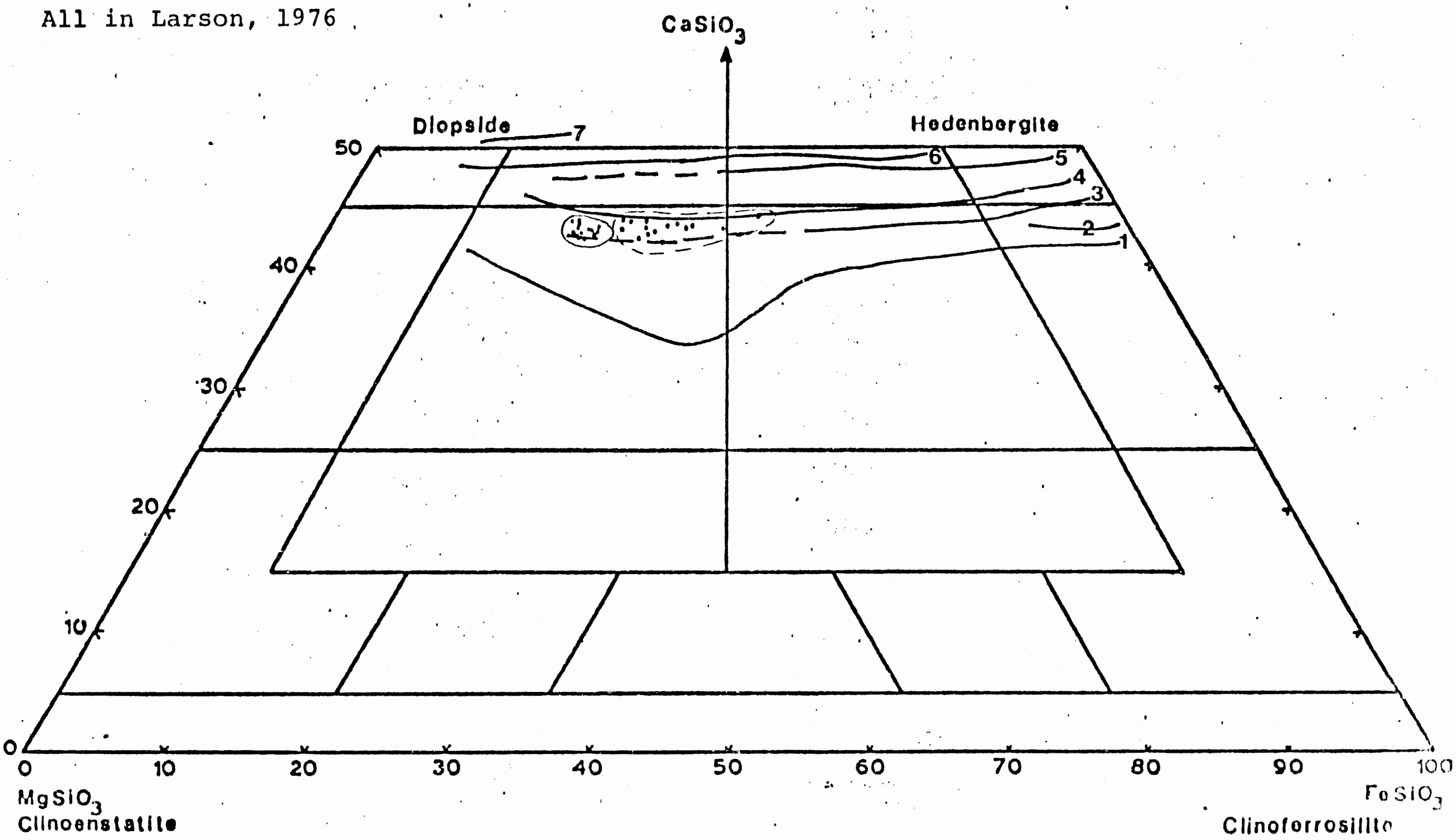
$$F_1 = (-0.012 \times SiO_2) - (0.0807 \times TiO_2) + (0.0026 \times Al_2O_3) - (0.00_{x}2 \times FeO) - (0.0026 \times MnO) + (0.0087 \times MgO) - (0.0128 \times CaO) - (0.0419 \times Na_2O)$$

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

FIGURE 5.4 - Comparison of several well established pyroxene crystallization trends with the rough trend formed by the metabasite and St. Alphonse gabbro pyroxenes. Note this rough trend is very similar to trends 3 and 4 both of which are typical trends of mildly alkaline magmas.

1) Skaergaard intrusion (Brown and Vincent, 1963)
2) Pantellerites (Nicolls and Carmichael, 1969)
3) Kungnat Intrusion (Upton, 1960)
4) Shiant Isles Sill (Gibb, 1973)
5) Ilimaussaq Intrusion (Larson, 1976)
6) Shonkin Sag Laccolith (Nash and Wilkinson, 1970)
7) Uganda Nephelinites (Tyler and King, 1967)

All in Larson, 1976



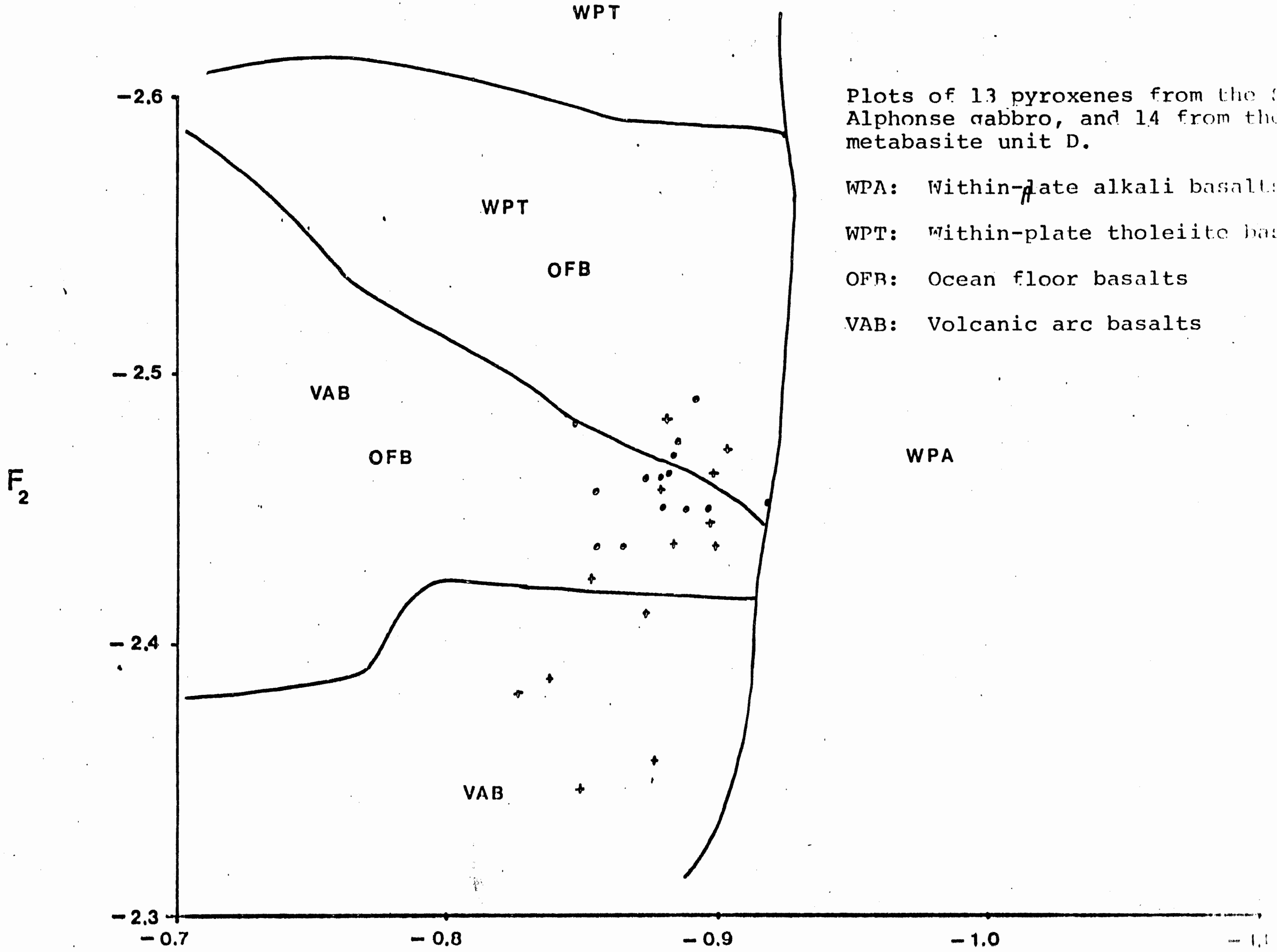
The discrimination achieved is based on differences in the bulk chemistry of the host magmas and in the partitioning of cations into the pyroxene lattice.

The plots of the pyroxene grains using the Nisbet and Pearce discrimination diagram have a wide scatter, falling mainly in the volcanic arc basalt (VAB) - ocean floor basalt (OFB) fields, and over the boundary of those fields with the within plate tholeiite (WPT) field figure 5.5). The plots of the average compositions of the pyroxenes, with error bars to two standard deviations, appear in figure 5.6. Thus the diagram suggests that the host basalts of the pyroxenes were either ocean floor basalts, volcanic arc basalts, or within-plate tholeiites. This suggestion is quite inconclusive, and again contrary to the more reliable trace element and REE discriminating techniques.

The unusual plot of the Cape St. Mary and St. Alphonse pyroxenes may be due to the fact that the Nisbet and Pearce (1977) method of discriminating tectonic environments has an overall success rate of only 69.5%. They found that the greatest success rate is for the within plate alkali basalts (89%), but the WPA field is only based on 82 samples, which may not be statistically valid on a worldwide basis.

A comparison of the average clinopyroxene composition of metabasite unit D from Cape St. Mary with the average clinopyroxene composition of WPA basalts compiled by Nisbet and Pearce (1977) reveals some significant differences, which can explain the unusual plot of the pyroxene pheno-

FIGURE 5.5 - Diagram after Nisbet and Pearce (1977)



Plots of 13 pyroxenes from the St. Alphonse gabbro, and 14 from the metabasite unit D.

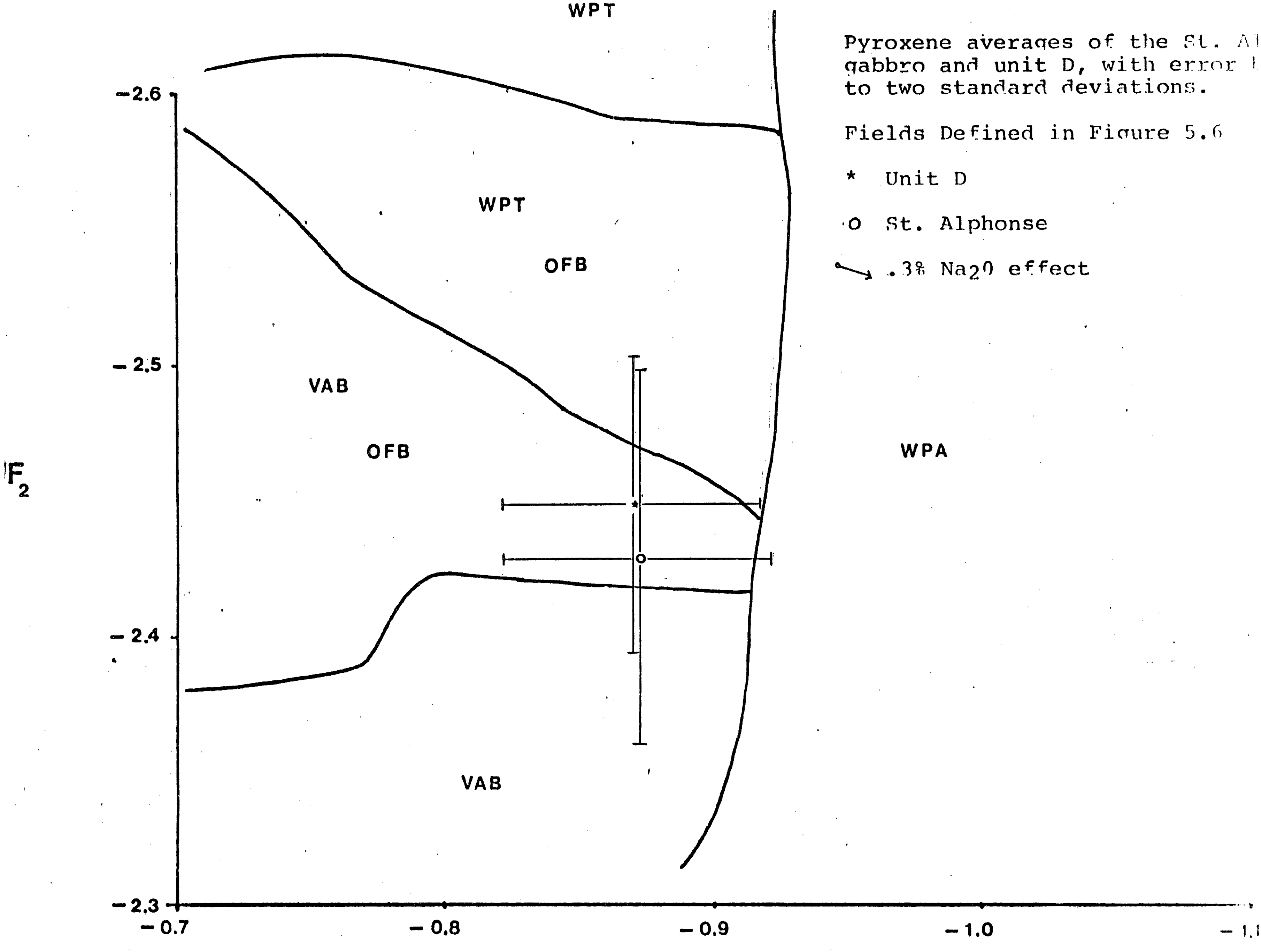
WPA: Within-plate alkali basalts

WPT: Within-plate tholeiite basalts

OFB: Ocean floor basalts

VAB: Volcanic arc basalts

FIGURE 5.6 - Diagram after Nisbet and Pearce (1977)



Pyroxene averages of the St. Alphon
gabbro and unit D, with error bars
to two standard deviations.

Fields Defined in Figure 5.6

* Unit D

o St. Alphonse

→ .3% Na_2O effect

1

crysts (table 5.1). Nisbet and Pearce indicate that identification of within-plate alkali basalts is most likely to be successful because their pyroxenes characteristically have high Na and Ti and low Si contents. However, the pyroxenes from the Cape St. Mary metabasite (unit D) are notably low in TiO_2 (1.37% vs. 1.77% in WPA), Al_2O_3 (1.79% vs. 4.10 % in WPA), and Na_2O (0.3% vs. 1.17% in WPA).

If an alkalic parentage of the metabasites is accepted, the extremely low amount~~s~~ of Na_2O is highly unusual, as the importance of this element on the F_1 eigen vector of the Nisbet and Pearce diagram is quite evident, (-0.0419 x Na_2O). One possible explanation for the "wrong" plots of the pyroxenes of this study is that Na_2O has been removed from the clinopyroxenes, perhaps during the albitization of plagioclase. Assuming pre-metasomatic Na_2O concentrations in the Cape St. Mary and St. Alphonse clinopyroxenes of the magnitudes used by Nisbet and Pearce (1.17% Na_2O in WPA), the effect would be sufficient to place the majority of the analyses into the WPA field. It should be noted that the electron microprobe used in this study has a lower detection limit of .3% for Na_2O (R. M. MacKay, personal communication). This small, undetectable amount of Na_2O, if present, would have a noticeable effect on the positions of the analyses. The magnitude of the effect of .3% Na_2O is shown by the arrow in figure 5.6.

That amount of Na_2O is insufficient to place the average compositions of the pyroxenes into the WPA field, but would place part of the F_1 error bar of each average pyroxene composition into that field.

These major element deficiencies in the clinopyroxenes would explain the low negative values on the first function (F_1), which is dominated by TiO2, CaO, and Na2O. Although the clinopyroxenes in the metabasite appear unaltered, the low Na_2O content and the other major element deficiencies in the clinopyroxenes could indicate a considerable metamorphic-metasomatic modification of the pyroxene chemistry, which would render discrimination diagrams utilizing pyroxene chemistry unreliable.

The element deficiencies in the clinopyroxenes of the metabasite could also have occurred during the cooling of the lava, for recent examinations of pyroxene chemistry (Gamble and Taylor, 1980, Coish and Taylor, 1979) have indicated that the element content of pyroxenes can be substantially affected by cooling rates of the hot basalt. The partitioning of Al and Ti into pyroxenes appears to be particularly affected by cooling rates. Coish and Taylor (1979) noted that Ti and Al contents are higher in pyroxenes from the chilled margins of a 15.6 meter thick mid-ocean ridge basalt flow than in those from the interior regions, although there is no systematic change in the pyroxene major element concentrations. They reported the average TiO_2

and Al_2O_3 contents for pyroxenes in the margins of the flow as 1.75% and 5.0% respectively, and 1.25% and 3.0% respectively for pyroxenes from the interior of the flow. Variations of this magnitude could affect the F_1 discriminant function of the Nisbet and Pearce diagram as much as 29%, and the F_2 discriminant function by as much as 33%. As rapid cooling appears to increase the Ti and Al contents of pyroxenes, the pyroxenes of a basalt could be expected to be displaced towards lower F_1 and F_2 values from chemically similar pyroxenes of a slow cooling, parental magma. This is a possible explanation for the slightly displaced positions of the metabasite clinopyroxenes from the gabbro clinopyroxenes on the Nisbet and Pearce diagram.

The Nisbet and Pearce discrimination diagram is at least useful for indicating that the clinopyroxenes from the St. Alphonse gabbro and the metabasite unit D of Cape St. Mary are of different compositions than the pyroxene composition usually expected for alkali basaltic magmas. This is reinforced by the SiO_2 versus TiO_2, and SiO_2 versus Al_2O_3 plots of pyroxene compositions (figures 5.2 and 5.3). The SiO_2 versus Al_2O_3 diagram of LeBas (1962) illustrates the low Al_2O_3 content of the clinopyroxenes, which causes them to be classified as hosted by subalkaline basalts.

Conclusion

Electron microprobe analyses reveal the pyroxenes in metabasite unit D to be calcic augites, and the pyroxenes in the St. Alphonse gabbro to range from calcic augites to slightly salitic in composition. A rough trend line formed by the pyroxenes from the two rock units closely resembles the pyroxene crystallization trend of mildly alkaline rocks.

A comparison of the chemistr~~ies~~y of the pyroxenes with the average composition of within-plate alkali basalt pyroxenes reveals some notable differences. The pyroxenes are notably low in TiO_2, Al_2O_3, and Na_2O, which could possibly be due to cooling rates and metasomatism.

The use of pyroxene chemistry on the Nisbet and Pearce diagram proved inconclusive in attempting to identify the paleotectonic environment of the metabasites of Cape St. Mary. This confirms the suggestion by Wark and Clarke (1980) that the diagram is not very successful as a discriminator of paleotectonic environments.

CHAPTER VI - CONCLUSIONS AND PALEOTECTONIC ENVIRONMENT

A field and petrographic examination of the White Rock Formation exposed at Cape St. Mary has revealed it to be composed of a basal metafelsite unit of probable ash flow (ignimbrite) origin, followed by four metabasite units of probable basaltic flow origin. The original igneous nature of the metavolcanics can only be demonstrated through discriminating techniques using the elements TiO_2 and P_2O_5, the trace elements Th, Hf, and Ta, and the REE's. THESE ELEMENTS all suggest that the metavolcanics are of alkalic parentage, and therefore possibly related to an alkali basalt-hawaiite-mugearite-benmorite-trachyte differentiation trend. A possible confirmation of such a trend is provided by the roughly defined crystallization trend formed by the pyroxenes from the uppermost metabasite (unit D) and the St. Alphonse gabbroic plug, which is seen to closely resemble the pyroxene crystallization paths of mildly alkaline magmas.

The present study demonstrates that the St. Alphonse gabbroic plug is closely related to the metabasites at Cape St. Mary, both geochemically and chronologically. REE data and pyroxene chemistry suggest the gabbro is slightly more evolved than the metabasites, and as such, is probably not a feeder for the observed metavolcanics. The gabbro could be, however, a feeder for slightly more evolved volcanics which were once overlying the exposed rocks at Cape St. Mary. Correlations with the more extensive Yarmouth White Rock Formation support the possibility of such a mode of origin.

The petrography and geochemistry of the basal metafelsite reveal it to be the product of a magma geochemically unrelated to the metabasites. The strongly fractionated, typically rhyolitic REE pattern of the metafelsite indicates that it is probably related to a tholeiitic-rhyolitic trend of basaltic differentiation.

Paleotectonic Implications

The existence of the bimodal volcanic suite and shallow-water sedimentary rocks of the White Rock Formation above the deep water sedimentary rocks of the Meguma Group indicates a drastic change in the paleotectonic setting of southern Nova Scotia during the Lower Paleozoic. Parts of the White Rock Formation (the central and northern Annapolis Valley exposures) were evidently deposited under shallow marine conditions, as indicated from the combined occurrence of carbonate oncolites, phosphates, pillow basalts, and shelly fossils (Lane, 1980). At Cape St. Mary, a shallow water, perhaps sand bar or beach type sedimentary environment, is suggested by the massive and cross bedded psammitic rocks. Subaerial volcanism at Cape St. Mary is indicated by the probable ash-flow origin of the metafelsite, and the absence of pillows in the metabasites.

The conclusions from the reliable Th-Hf-Ta discrimination diagram and the moderately reliable TiO_2-K_2O-P_2O_5 diagram suggest that the volcanism occurred in a within-plate environment. Lane (1980) concluded that the erosion of quartz arenite lithologies underlying parts of the White Rock Formation volcanics indicate contemporaneous active faults existed. The volcanism could have been centered along these faults. The suggestions of within continental rhyolitic and alkali basaltic volcanism, possibly related to faulting, is supported by the correlations with the more extensive White Rock metavolcanic sequence in the Yarmouth syncline. Sarkar (1978) proposed the White Rock volcanism at Yarmouth to be the result of failed continental rifting.

If Woods' (1980) contention that the Ta-Hf-Th diagram is a good indicator of paleotectonic environment can be demonstrated to be reliable, the location of the Cape St. Mary White Rock metavolcanics in the within-plate alkali basalt field and the transitional nature of the Yarmouth metavolcanics may be taken to indicate that crustal thickness during the White Rock time increased from Yarmouth to Cape St. Mary.

Recommendations for Future Work

Similar examinations of the petrology, phase chemistry, and major and minor trace element geochemistry of metavolcanic rocks in the White Rock exposures of the Annapolis Valley would be fruitful and could lead to geochemical correlations of the metavolcanics extending beyond those suggested for Cape St. Mary and Yarmouth areas.

An examination of the other pre-deformational mafic intrusives near the southern White Rock exposures (e.g., Lake Wentworth diorite) could shed more light on the actual style of eruption, the paleotectonic environment, and reinforce the genetic relationships of these intrusives to the White

Rock metavolcanics.

Geochemical investigations of the Annapolis Valley White Rock exposures would be useful in complying with the suggestions of a westward thickening of the Silurian crust, which is indicated by the Ta-Hf-Th diagram. This would have considerable significance for Lower Paleozoic paleography and paleotectonics.

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APPENDIX

Sample Selection and Preparation

The geochemical samples of the metavolcanics were taken from "least altered" parts of the units, and the sample of the St. Alphonse gabbro was taken from the least altered, central part of the intrusion. In all cases, large samples (1-1.5 kg.) were taken to ensure sample homogeneity. Any weathered rinds were discarded, and surfical contaminents were removed by washing and rinsing. Fragmentation of the bulk samples was done in a hydraulic press, and crushing was done in a ceramic jaw crusher. The crushed samples were powdered in a tungsten carbide swing mill, and homogenized in cleaned plexiglass tumblers for 2 hours. The homogenized powders of each sample were stored in plastic vials.

Analytical Methods

Six samples were analysed, together with the U.S.G.S. rock standards AGV-1 and BCR-1 as known standards, and two unknown standards 79-9 and 79-10, supplied by Dr. G. K. Muecke. These standards were used in the "conventional" analyses, but not in the electron microprobe analyses.

I. Whole Rock Analyses

The whole rock analyses were conducted on fused sample powders by a Cambridge Mark 5 Electron Microprobe. Operating conditions were 15 Kv with a 5 nanoamperes sample current (100 second counting time). An on-line EDATA 2 computer program after Smith et al (1980) was used for the data processing. Precision data for the electron microprobe is given in Figure A.1.

Each whole rock microprobe analysis rastered an area of 50 x 50 microns. The whole rock analyses done soley by microprobe is reported in Table A.1.

The sample glasses were produced from a small amount (~200 mg) of powder which was fused by passing a current through a .1mm x 1.5cm x 5 cm Mo strip. To prevent sample oxidation, the fusions were done in a chamber evacuated of air, and filled with N_2. The glasses were carefully removed from the Mo strip, and then mounted and polished in an epoxy resin base.

As the volatiles (H_2O+, H_2O-, CO_2) are lost upon sample fusion, they must be incorporated into the whole rock analysis before it can be considered complete. Fe_2O_3 and FeO must also be incorporated into the whole rock analysis as the microprobe only analyses iron as FeO total.

Incorporation of volatiles, ferrous iron, and ferric iron into the whole rock analysis were done in the following manner.

1. Fe_2O_3 calculation:

(Total iron as FeO from microprobe) x gravimetric
(- iron as FeO by titration) conversion =
W.T. % Fe_2O_3
(1.1113)

2. Add FeO W.T. % (probe) and Fe_2O_3 W.T. % (From #1) into microprobe analysis

3. Subtract total weight percent of the volatiles from the microprobe analysis.

4. recalculate microprobe analysis to total reached in #3, and add on volatiles.

To provide a control as to the accuracy of this method of whole rock analysis, the rocks were also analysed by the following "conventional" methods.

1. Seven major elements (Al, Fe(total), Mn, Mg, Ca, K, Na) were analysed by means of a Perkin-Elmer 503 Atomic Absorbtion Spectrometer. Sample decomposition was modified after the method of Warren and Caster (1975).

2. FeO was determined titrimetrically. The calculation used for determination of FeO and Fe_2O_3 are as follows:

$$\%FeO = \frac{(\text{ml. for sample} - \text{ml. for blank})}{\text{sample Wt. in gm.}} \times 0.00359 \times 100$$

$$\%Fe_2O_3 = FeO\ (\text{total}) - (1.113 \times FeO)$$

3. P_2O_5 was determined colorimetrically. Optical densities of the prepared sample solutions and sample blanks were measured at 827 mu on a Bausch and Lomb Spectronic model 70 spectrophotometer.

4. H_2O+ was determined using the Penfield tube method after Volborth (1969), with anhydrous sodium tungstate as a flux.

H_2O- was determined by the differences in the sample weight before and after the sample was dried in an oven at 110 degrees for 24 hours.

5. CO_2 analysis was conducted by acid evolution, and determination by automatic titrator (Leco Corp., Model 532), using sodium methylate as the titrant. The analytical results from the "conventional" methods are reported in table A.2.

II. REE and Trace Element Analyses

The analysis of Ba, Co, Cr, Cs, Sc, Ta, Th, U, and REE in all samples was conducted by instrumental neutron activation analysis (INAA), with AGV-1 and BCR-1 as standards. The method used for the analyses is adopted from Gordon et al (1968), and is outlined by Gibson and Jagam (1980). Precision data for INAA (Ila, et al, 1980) is given in Table A.3.

III. Mineral Analyses

The electron microprobe at Dalhousie University was used to analyse the pyroxenes in polished thin sections for the St. Alphonse gabbro and unit D.

FIGURE A.1 - Precision Data for the Electron Microprobe at Dalhousie University. (Courtesy of R. M. MacKay).

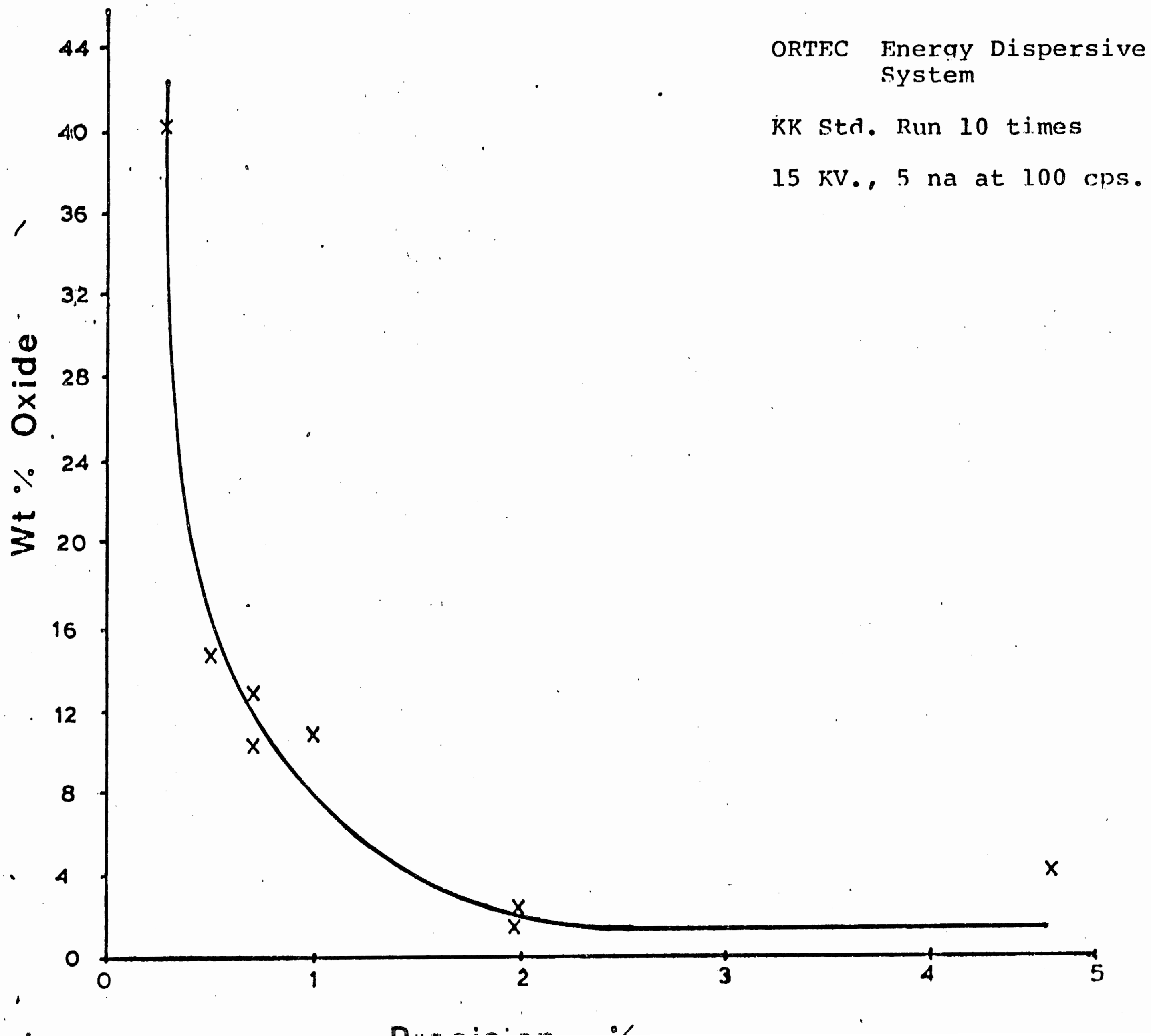

TABLE A-1

WHOLE ROCK ANALYSIS* BY ELECTRON MICROPROBE

	79-4	S	%S	79-6	S	%S	79-9	S	%S
SiO_2	46.76	0.31	0.66	49.62	0.54	1.09	79.26	1.48	1.87
TiO_2	3.10	0.14	4.52	3.30	0.21	6.36	0.27	0.13	48.15
Al_2O_3	15.32	0.19	1.24	14.30	0.62	4.34	9.53	0.57	5.98
FeO	14.19	0.25	1.76	15.00	0.66	4.40	3.24	0.09	5.86
MnO	0.15	0.06	40.00	0.26	0.03	11.54	0.05	0.05	100.00
MgO	6.48	0.19	2.93	2.65	0.17	6.42	1.32	0.03	6.06
CaO	8.71	0.18	2.07	7.70	0.22	2.86	2.27	0.10	4.41
Na_2O	2.92	0.11	3.77	4.24	0.19	4.48	3.10	0.30	9.68
K_2O	0.97	0.06	6.19	1.53	0.08	5.23	1.00	0.13	13.00
P_2O_5	0.84	0.07	8.33	1.91	0.14	7.33	0.16	0.14	87.50
S	0.57	0.15	26.32	0.52	0.14	26.92	0.04	0.08	200.00
TOTAL	100.01			100.67			100.24		

Table A-1 continued
Whole Rock Analysis by Electron Microprobe

	79-10	S	%S	79-11	S	%S	79-12	S	%S
SiO_2	49.42	0.50	1.01	43.81	1.15	2.26	46.95	0.94	2.00
TiO_2	4.02	0.05	1.24	3.15	0.16	5.08	3.08	0.08	2.60
Al_2O_3	17.35	0.10	0.58	15.72	0.40	2.54	15.10	0.23	1.52
FeO	18.77	0.25	1.33	13.43	0.57	4.24	13.08	0.27	5.50
MnO	0.06	0.05	83.33	0.19	0.08	42.11	0.17	0.06	35.29
MgO	3.59	0.03	0.34	6.40	0.32	5.00	6.34	0.34	5.36
CaO	1.96	0.09	4.59	12.72	0.16	1.26	11.10	0.31	2.79
Na_2O	2.28	0.12	5.26	2.77	0.12	4.33	1.03	0.10	9.71
K_2O	0.88	0.03	3.41	0.80	0.07	8.75	1.41	0.11	7.80
P_2O_5	1.06	0.05	4.72	0.44	0.09	20.45	0.59	0.05	8.47
S	0.90	0.25	27.78	0.44			1.00	0.52	52.00
TOTAL	100.39			99.87			99.58		

*79-4, 79-6, 79-10, 79-11, and 79-12 are averaged from 6 analyses each 79-9 is averaged from 10 analyses

TABLE A.2

WHOLE ROCK ANALYSIS BY A.A.

	79-4	79-6	74-9	79-10	79-11	79-12
SiO_2	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
TiO_2	2.83	2.98	0.29	3.69	2.59	2.54
Al_2O_3	15.35	14.18	8.60	15.61	13.52	13.02
Fe_2O_3	2.83	3.84	N.D.	1.34	1.70	1.72
FeO	10.62	11.13	2.99	15.43	9.75	9.62
MnO	0.10	0.24	0.05	0.11	0.12	0.18
MgO	6.22	2.36	1.16	3.17	5.59	8.92
CaO	8.48	6.99	2.12	1.73	10.76	9.73
Na_2O	2.97	4.16	2.73	1.94	2.50	0.98
K_2O	1.09	1.63	1.01	0.95	0.82	1.42
P_2O_5	0.60	1.41	0.09	0.77	0.34	0.45
H_2O+	2.96	2.07	0.82	4.29	4.82	5.32
H_2O-	0.08	0.25	0.19	0.32	0.10	0.51
CO_2	0.26	N.D.	5.79	0.68	0.18	4.76

Table A.2 continued

Whole Rock Analysis by A.A.

	BCR-1	JB-1	79-9 unknown standard	79-10 unknown standard
SiO_2	N.A.	N.A.		
TiO_2	2.26 (2.22)	1.31 (1.34)	0.27 (0.27)	3.81 (3.75)
Al_2O_3	13.60 (13.68)	14.60 (14.62)	14.21 (14.20)	8.59 (8.56)
Fe_2O_3	3.31 (3.48)	2.08 (2.36)	0.21 (0.37)	7.71 (8.23)
FeO	9.07 (9.05)	6.16 (6.02)	1.69 (1.62)	9.06 (8.60)
MnO	0.18 (0.19)	0.16 (0.15)	0.06 (0.06)	0.17 (0.17)
MgO	3.48 (3.49)	7.75 (7.76)	0.74 (0.76)	12.77 (13.51)
CaO	6.92 (6.98)	9.42 (9.35)	2.08 (2.17)	14.78 (14.72)
Na_2O	3.29 (3.29)	2.77 (2.79)	3.50 (3.39)	0.67 (0.71)
K_2O	1.74 (1.68)	1.42 (1.42)	3.92 (3.96)	0.27 (0.18)
P_2O_5	0.36 (0.33)	0.26 (0.26)	0.09 (0.09)	0.06 (0.07)
H_2O+	N.A.	N.A.		
H_2O-	N.A.	N.A.		
CO_2	N.A.	N.A.		

N.D. = Not Detected
N.A. = Not Analysed A.A. accepted values for the USGS rock standards and the unknown standards (supplied by Dr. G. K. Muecke) are bracketed.

"Accepted" values for BCR-1 and JB-1 are from Abbey (1977).

TABLE A.3 - INAA PRECISION DATA

Element	Percent Standard Deviation
La	0.5
Ce	7.1
Sm	1.5
Eu	3.1
Tb	4.2
Yb	6.2
Lu	3.7
Ba	5.4
Co	3.5
Cr	8.8
Cs	5.3
Hf	3.7
Sc	3.5
Ta	7.5
Th	4.7