

**MAGMA MIXING
IN THE CADILLAC MOUNTAIN INTRUSIVE COMPLEX
SOMMES COVE, MOUNT DESERT ISLAND, MAINE**

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ABSTRACT

Mount Desert Island, located off the southern coast of Maine, is dominated by the Silurian Cadillac Mountain Intrusive Complex (CMIC), one of many plutons within the Coastal Maine Magmatic Province (CMMP) (HOGAN and SINAH, 1989). The major phase of the CMIC is the Cadillac Mountain Granite (CMG). It is bounded on the west by a complexly layered Gabbro-Diorite unit (G-D) (WIEBE, 1993) which has excellent exposures along the coastal inlets and bays of the island. The G-D unit is suspected of being the result of magma mixing (WIEBE and CHAPMAN, 1993). In order to examine this hypothesis, a study conducted during June of 1993 in Sommes Cove, Mount Desert Island (MDI in Figure 1) involved mapping detailed field relations and gathering samples for petrographic and geochemical analysis. These data allowed the determination of crystallization histories and petrogenetic relationships between the various rock types within the unit, and in particular within Sommes Cove.

Field relations in the layered section of Sommes Cove strongly suggest the interaction between magmas. Chilled gabbroic layers, in close association with more felsic, heterogeneous units, grade to coarse gabbro. This implies a non-isothermal relationship, thus eliminating liquid immiscibility and undermining simple magmatic differentiation. Tabular biotite within the felsic unit near the contact is parallel to the boundary, appearing flow laminated; biotite within the chilled margins of the mafic unit is also flow laminated. Lamination in both units controlled by the contact between them strongly suggests that both were liquid when they came in contact.

Macroscopic and petrographic mineral assemblages and textures provide abundant evidence for the interaction of magmas in the G-D unit.

Intermediate layers consist of mafic and felsic glomerophyrocysts several millimeters across, and display textures that imply disequilibrium conditions, such as partially resorbed and zoned plagioclase and rapakivi quartz and kspars xenocrysts. Geochemical data support the petrography and field relations. Several major oxides plotted against silica conform well to linear mixing trends, and trace element modeling indicates magmatic differentiation is an inadequate explanation for the observed chemistries.

Tectonic discrimination diagrams classify the granitic unit of Sommes Cove as a peraluminous, subalkaline within-plate granitoid, consistent with the A-type classification of the Cadillac Mountain Granite. The basaltic dikes may be tholeiitic basalts, and both the granite and the basalt plot near rift tectonic fields. Although the exact timing of the pluton's emplacement in relation to regional tectonics is not fully resolved, HOGAN AND SINAH (1989) have suggested extension of the crust as a possible model for magmatism in the area.

The model proposed by WIEBE (1993) for the layered sequence of the CMIC states that it formed from periodic infusions of basic magma into a granitic magma chamber. This mechanism explains well the field, petrographic, and geochemical relations of Sommes Cove.

CHAPTER ONE

INTRODUCTION

Off the southern coast of central Maine sits Mount Desert Island (MDI), a glaciated assemblage of Silurian intrusive igneous units known collectively as the Cadillac Mountain Intrusive Complex (CMIC) (Figure 1-1). The CMIC is a well-studied complex, certainly due in part to the excellent exposures of all units both inland and in the coastal inlets and bays. It is a member of the Coastal Maine Magmatic Province (CMMP), a collection of over 100 mafic, felsic, and bimodal Ordovician-Devonian plutons formerly called the Bays-of-Maine complex (CHAPMAN, 1962). These plutons intrude a complex assemblage of several fault-bounded lithotectonic terranes, several small "microplates" of continental crust accreted onto the North American craton during the Acadian Orogeny (HOGAN and SINAH, 1989). The timing of terrane accretion is not fully resolved, although it has been constrained to Late Silurian and Early Devonian. While the majority of the CMMP's plutons appear to result from post-Acadian regional extension, the CMIC of Mount Desert Island may be pre-Acadian (WIEBE, 1993b).

Magmatism on MDI is distinctively bimodal in character, displaying mafic and felsic units. An intricately layered gabbro-diorite-granite unit (G-D) forms the western border of the island (Figure 1-2). The Cadillac Mountain Granite (CMG), a hypersolvus, hornblende granite, comprises the bulk of the CMIC. The Sommesville pluton, a biotite-bearing, two feldspar granite, intrudes the central portion of the island between the CMG and the G-D unit. Additional intrusive units include the Southwest Harbor granite and the northern gabbro. The volcanics of the Cranberry Island Series (of unknown

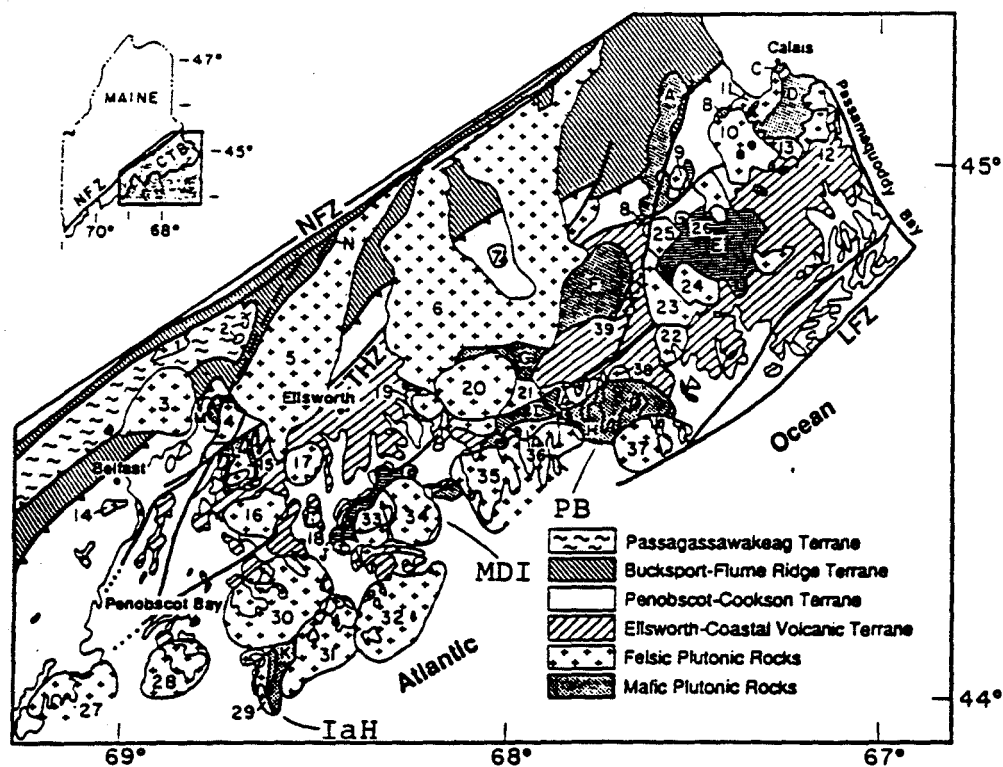


FIGURE 1-1: Geologic map of the Coastal Maine Magmatic Province. Mount Desert Island (MDI) is located near the center of the map (from HOGAN and SINAH, 1989).

origin) form the southern portions of Mount Desert Island and the Cranberry Isles south of the island.

The CMIC intrudes the unconformity between two major basement rock units: the Cambrian-Ordovician Ellsworth schist and the Early Silurian Bar Harbor Formation (GILMAN et al., 1988). The lower greenschist facies Ellsworth schist comprises much of the south-central coast of Maine and is the northernmost unit of Mount Desert. Additional schist crops out at the southern contact of the layered G-D unit, north of the Southwest Harbor granite. The Bar Harbor Formation, a thick package of marine sediments, rims the eastern to southern borders of the island, and provides the xenoliths for an intrusive breccia unit in contact with the CMG.

The areal extent of the exposed CMIC is an oval roughly 14 by 20 km (WIEBE, 1993b). Field relations, backed by geophysical data, suggest the CMG is approximately 3 km thick and saucer shaped. Gravity data also suggest the G-D unit extends below the Sommesville and Cadillac Mountain granites, forming a lensoid body 2-3 km thick (Figure 1-3) (HODGE et al., 1982 in WIEBE, 1993b).

Different authors ascribe different ages to the CMIC, ranging from 420 ± 5 Ma (SEAMAN and RAMSEY, 1992) to 361 ± 35 Ma (HOGAN and SINAH, 1989). The most recent age uses Ar-Ar ratios and dates the layered gabbro-diorites to 418 ± 5 Ma (WIEBE, 1993b). The age discrepancy, though not particularly significant to the aims of this research, does have important tectonic implications. The Acadian Orogeny, constrained by HOGAN and SINAH (1989) and LUDMAN (1986) to the Late Silurian - Early Devonian, is the most important orogeny in the northeastern United States of the early-mid Proterozoic, and is thought to be the result of numerous "microplates" accreted onto the North American craton. The most recent date of 418 ± 5 Ma

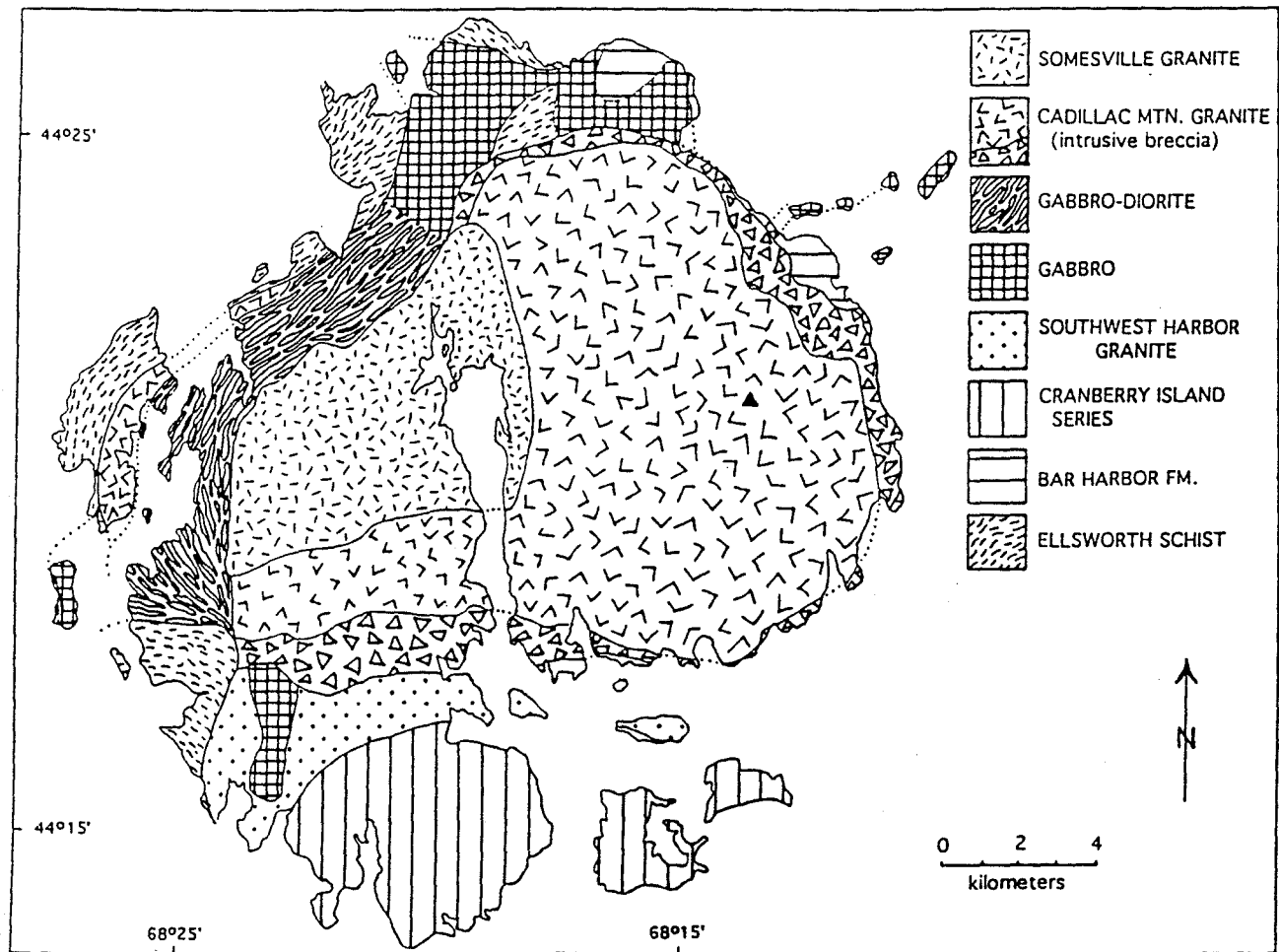


FIGURE 1-2: Geologic map of Mount Desert Island. The layered gabbro-diorite unit forms the west-central border of the island (from WIEBE, 1993b).

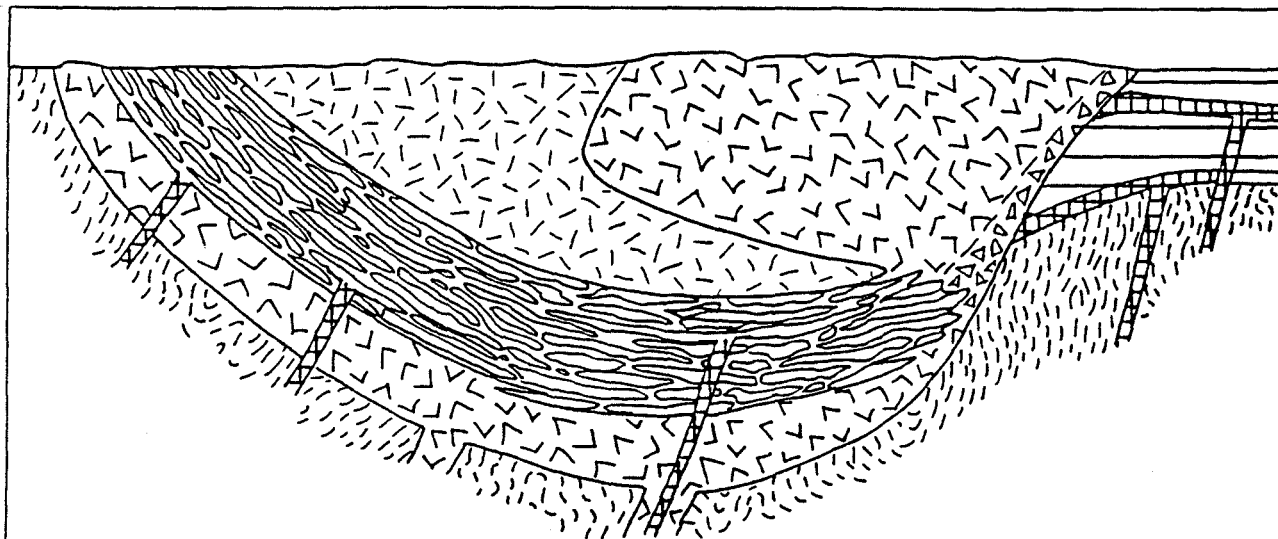


FIGURE 1-3: East-west cross-section through the Cadiillac Mountain Intrusive Complex. Unit symbols are the same as for Figure 1-2 (from WIEBE, 1993b).

for the CMIC implies the CMIC is pre-Acadian. This not only is atypical for plutons of the region, but also raises two questions: 1) how did the CMIC form if not by the post-Acadian extension as suggested by HOGAN and SINAH (1989) for most of the CMMP and 2) why is there no metamorphic/compressional imprint on the CMIC from the later Acadian event. These questions are currently unanswered, although the CMIC could have avoided major tectonic imprinting if the dominant fault motion of the region were strike slip (R.A. WOBUS, personal communication, 1993). Also, as a shallow intrusion relatively rigid as compared to the surrounding sediments, it may have had little susceptibility to metamorphism.

CURRENT RESEARCH

This research focuses on the excellent exposures of the layered G-D unit in Sommes Cove, a small bay on the western edge of the island (Figure 1-4).

Its objectives:

- Detailed field description of the layered sequence in Sommes Cove
- Detailed petrographic descriptions of the rock types of the G-D unit
- Geochemical analysis of the major rocks
- Identification of magma mixing/mingling features and their mechanisms, both macro and microscopic
- Determination of the role of mixing/mingling in the crystallization histories of the various rocks
- Determination of the most viable felsic and mafic end-member compositions for the formation of the hybrid rock types seen
- Assessment of different igneous layering models, including one suggested by WIEBE (1993a, 1993b), for the formation of the layered G-D unit.

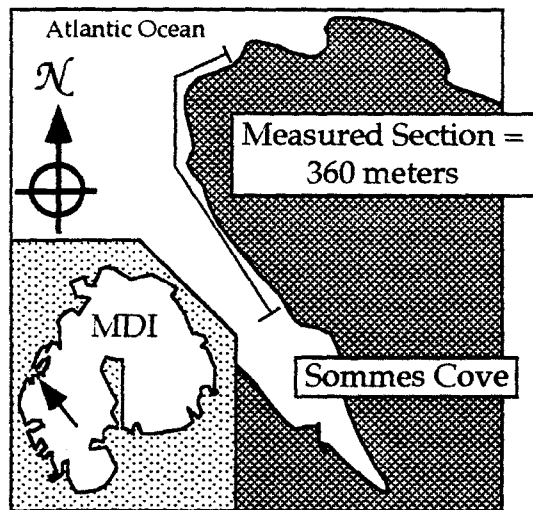


FIGURE 1-4: Sommes Cove field area on the western coast of Mount Desert Island (MDI). The shaded region is the island, the white is the ocean.

PREVIOUS WORK

Cadillac Mountain Intrusive Complex

CHAPMAN (1970) provided some of the most comprehensive descriptions and maps of Mount Desert Island. GILMAN et al. (1988) revised CHAPMAN'S work in preparing the Visitor's Guide to the Geology of Acadia National Park, a lay person's guide which included the basement rock map used for this research. This guide describes all of the sedimentary, volcanic, and plutonic units of the MDI, including the "irregular layering" in the gabbro-diorite unit. The two rock types of the G-D unit are considered "closely related in origin," and are described as "intermixed over short distances." No explicit reference, however, is made to mixed magmas. These authors consider the gabbros as older, later intruded by the more felsic units.

Magma Mixing in the CMIC

Many authors have recognized the importance of magma mixing in the crystallization history of the CMIC. HOGAN and SINAH (1989) classified the CMG and Sommesville granite as two of many felsic plutons in the CMMP with significant mafic magmatic interaction. They cited the presence of evenly distributed, small mafic enclaves throughout these plutons as the most diagnostic feature. SEAMAN and RAMSEY (1992) presented a detailed analysis of these enclaves, also considering them a consequence of magma mixing. WIEBE (1993b) interpreted these enclaves as small pieces of the mafics within the G-D unit, carried up into CMG chamber through convective processes, an important aspect of his model for the CMIC, discussed in greater detail below.

TAYLOR et al. (1980) analyzed numerous composite dikes on Mount Desert Island previously recognized by CHAPMAN (1962), ultimately

concluding the dikes were the result of petrogenetically unrelated coexisting felsic and mafic liquids. They discarded the liquid immiscibility theory, a thermal equilibrium process for dike formation, citing chilled margins as evidence for thermal contrast between the two end-member magmas. Embayed, replaced, and resorbed crystals in hybridized portions of the dikes, termed "skialiths," also suggested disequilibrium between end-members. Rare earth element (REE) enrichment patterns observed in the dikes are also inconsistent with immiscibility experiments; the granites of the dikes are richer in light REE's although bulk distribution coefficients for these elements favor basalt.

Wiebe Model

WIEBE (1993b) proposed a relatively comprehensive model for the formation of the G-D unit and its relation to the other CMIC units. The G-D unit represents the floor of the CMG chamber, where the growing leucocratic cumulate pile was repeatedly intruded by mafic replenishments. These intrusions varied in volume, those of smaller volumes remaining relatively contained and chilled on all margins. Larger influxes chilled only along the basal contact against the cumulate pile on which it rested, while the upper portions of the influx hybridized with the overlying felsic liquid to varying degrees through mixing, catalyzed by double diffusive convection. This convection, mentioned earlier, also carried some mafic material up higher into the chamber to form the observed enclaves. WIEBE asserts that the layering, and the many mingling and mixing structures seen in the G-D unit (and present as well in Sommes Cove, as will be described later) can be accounted for by his model.

CHAPTER TWO

FIELD WORK -- OBSERVATIONS

Sommes Cove, located along the central, western coast of Mount Desert Island, is found at longitude 68°25' and latitude 44° 19' on the Bartlett Island 7.5 minute USGS quadrangle. Outcrops display abundant glacial features, including striae, chatter marks, roches moutonnées, and large igneous and metamorphic erratics. The cove sits in the middle of the layered gabbro-diorite unit that comprises most the western coast, and which is interpreted as part of the original floor of the Cadillac Mountain magma chamber. This site was selected because it contains excellent outcrops (especially at low tide), abundant magma mingling structures in a well layered sequence, and a full range of compositions from gabbro to granite. Field work consisted of detailed documentation of rock types and their relationships, mapping and measurement of the entire field area, and sampling for petrographic and geochemical analyses. To aid the reader in visualizing field relations, all of the plates in this chapter and the following chapter (Petrography) are keyed to the stratigraphic column with capital letters.

ROCK UNITS

All of the outcrops of Sommes Cove become partially submerged by high tide waters, and are therefore somewhat obscured by resultant organics, debris, and weathering products. Epidote is ubiquitous. Therefore most identifications were based on the cleanest rocks, above the high water mark. I established five major igneous rock types while working in the field:

Basalt

A fine-grained intrusive, this unit comprises the late stage mafic dikes, and are not part of the layered section (Plate 2-1). The color of these dikes ranges from brown to black, and hand samples are comprised of homogeneous, aphyric plagioclase and pyroxene.

Pegmatite and Associated Aplite

These later, cross-cutting veins of large potassium feldspar and quartz crystals are recognized by their mineral assemblage and pink color (Plate 2-2). Aplites are commonly associated with pegmatitic dikes, and also occur in the felsic portion of a composite dike.

Gabbro

Dark gray, fine and coarse-grained gabbros form the most mafic units of the layered sequence. Fine-grained gabbros, enriched in the hydrous phases biotite and amphibole, commonly occur in contact with a more felsic unit, either "diorite" or granite (Plate 2-3). Coarser varieties of plagioclase, pyroxene, and secondary amphibole grade from the fine-grained gabbro, and commonly display felsic xenocrysts of k-spar and, less commonly, quartz. Quartz and k-spar xenocrysts exhibit "rapakivi" texture, rimmed by white plagioclase (Plate 2-4).

"Diorite"

This term encompasses the wide variety of observed intermediate rock units. (Actual classifications, determined later from petrographic point counts, include diorite, quartz monzodiorite, quartz monzonite, and two-feldspar granite.) These extremely heterogeneous units generally occur in



PLATE 2-1: Late stage basaltic dike with sharp, angular contacts.
Knife for scale.



PLATE 2-2: Cross-cutting pink aplite veins. Lens cap in upper center for scale.



PLATE 2-3: Cuspate, chilled gabbro in contact with intermediate unit.
'A' on stratigraphic column (Figure 2-2).



PLATE 2-4: Rapakivi kspar and quartz xenocrysts in coarse gabbro.
Pen for scale.

gradational contact with coarse gabbro (Plate 2-5). Plagioclase, alkali feldspar, and quartz form the primary minerals. Amphibole is the primary mafic phase, and biotite is also common. Large kspar phenocrysts, also commonly with plagioclase rims, sometimes outcrop in concentrations parallel to the dominant layering of the section, though this pattern is not common. Biotite and amphibole are concentrated at the contacts with gabbro.

Granite

A key feature to this field area, this unit is the most felsic of the sequence, and may most closely represent the host liquid's original composition (Plate 2-6). Only one layer was classified granite while in the field. This unit is generally aphyric, although finer grained mafic enclaves concentrate at the upper, gabbroic contact. Plagioclase, though not rare, is subordinate to larger kspar, and amphibole is the dominant mafic phase. The unit as a whole closely resembles the Cadillac Mountain Granite.

FIELD RELATIONS

The layered sequence in Sommes Cove is a complicated assemblage of the above units, with varying textures, thicknesses, and contacts. Although many contacts are highly irregular, plots of the measured layers on a stereonet ultimately showed that the dominant layering strikes N49W and dips 23° to the east. The southern third of the measured coastline is sub-parallel to the strike, and as expected this area is *relatively* consistent laterally, with layered units easily correlated across gaps or poor outcrops. However, because the coast here trends approximately N35-45W, there is still a distinct progression of layers displayed. To the northwest, the coastline angles to the northeast and more of the layered sequence is revealed as the coast cuts approximately



PLATE 2-5: Heterogeneous "diorite". Pen for scale.
'B' on stratigraphic column (Figure 2-2).



PLATE 2-6: Pink granitic unit underlying cusate gabbro layer. Note
intermediate unit sandwiched between the two. Lens cap for scale.
'C' on stratigraphic column (Figure 2-2).

perpendicular to layering. Using N49W, 23E as the dominant layering, 360 meters of measured coastline translates into 82.8 meters of true thickness. A detailed map (Figure 2-1) and stratigraphic column (Figure 2-2) constructed from this data illustrate this relationship. The top of the stratigraphic column was determined by orientation of diapiric upwellings, described in detail below.

Layered Sequence

Three major rock types comprise the Sommes Cove layered series. Heterogeneous, "dioritic" matrix dominates the sequence, and contains intercalated gabbroic and granitic layers of irregular spacing and thickness. Layers are laterally correlative, generally continuous (gabbroic layers are sometimes segmented), and range from 10 cm to 10's of meters in thickness (Plate 2-7). Contacts between layers are generally irregular, cusped, and indistinct, suggesting intermingling liquid-liquid interaction.

"Dioritic" Layers

Intermediate layers of highly variable texture and mode comprise the bulk of the Sommes Cove sequence. Compositions range from true diorites through two-feldspar granite, and almost everything in between. True diorite is rare, as almost all intermediate layers display free quartz. Amphibole is the most common mafic phase, though there are some relict pyroxenes. Although all intermediate layers are coarse-grained, only the more felsic units contain abundant, large potassium feldspar pheno/xenocrysts with white plagioclase rims ("rapakivi" texture).

"Dioritic" layers become increasingly leucocratic up-section, or northward, the consequence of a gradational increase in felsic character --

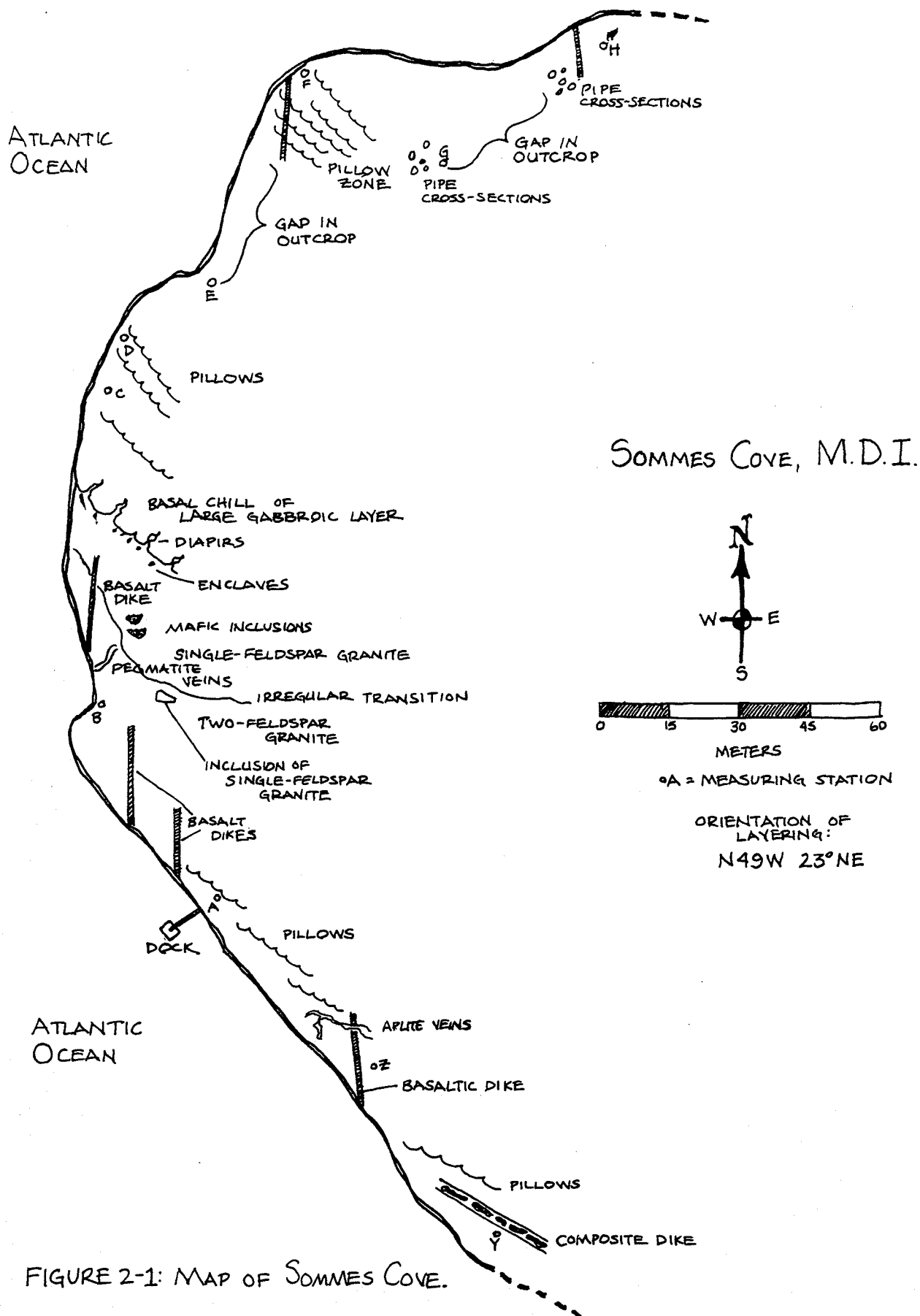


FIGURE 2-1: MAP OF SOMMES COVE.

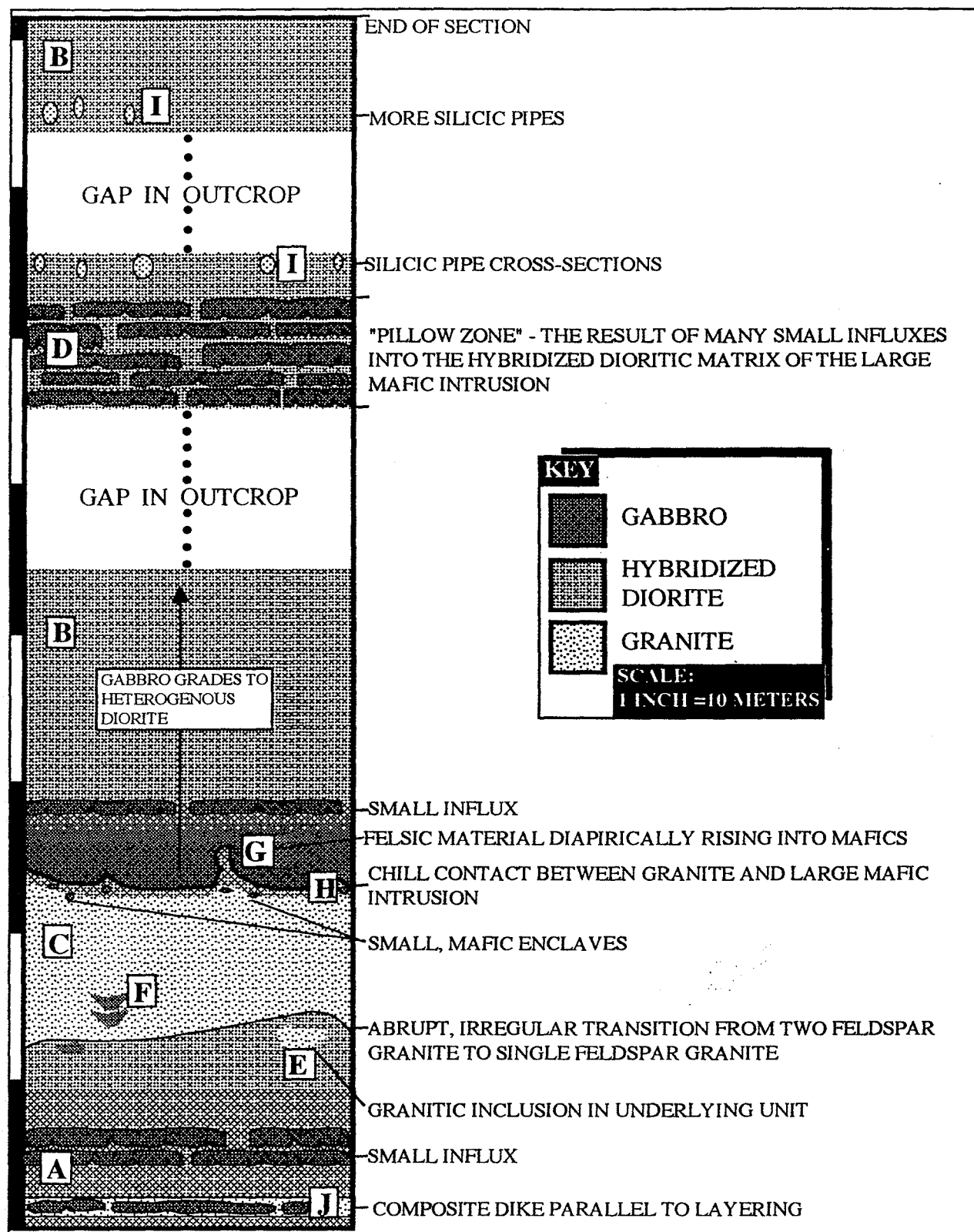


FIGURE 2-2: Schematic stratigraphic column of the Sommes Cove field area. Bold capital letters are keyed to plates in chapters 2 and 3. Total thickness=82.6 meters.



PLATE 2-7: Well developed gabbroic layers in coarser intermediate matrix. Knife for scale. 'D' on stratigraphic column (Figure 2-2).



PLATE 2-8: Single-feldspar granite inclusion within underlying two feldspar granite. Knife for scale. 'E' on strat column (Figure 2-2).

alkali feldspar and quartz percentages *generally* increase. The upper two-thirds of the measured sequence originates as a gabbroic layer with a basal chill that grades to quartz monzonite over a short distance. The lower third of the mapped area grades from quartz monzodiorite through a two feldspar granite unit, which has a non-planar, indistinct contact with the most felsic unit of the layered sequence.

The contact between the two-feldspar granite and the granitic unit displays particularly complex relationships (Figure 2-2). The transition itself is characterized by an abrupt decrease in the mafic minerals and plagioclase content, with an accompanying increase in quartz and kspar. Although subparallel to the dominant layering, the contact is highly irregular. A 1x2.5 meter inclusion of the overlying granitic unit sits within the underlying two-feldspar granite (Plate 2-8), approximately three meters below the transition. The inclusion has soft and curvilinear contacts. Potassium feldspar xenocrysts of the more felsic inclusion have been incorporated into the surrounding unit; the two-feldspar granite immediately surrounding the inclusion is substantially enriched in rapakivi kspar exactly similar to those contained within the inclusion (Plate 2-9). Two small, medium-grained inclusions with less quartz than the surrounding matrix in the two-feldspar granite have unknown origins. Within the upper granite of the transition sit two unusual mafic inclusions one meter in diameter. Chilled gabbro surrounds most of their perimeters, though one contact, of both inclusions, is more diffuse and coarser grained (Plate 2-10).

Gabbroic Layers

Coarse and fine grained gabbro occurs in both thick and narrow layers. Narrow, chilled gabbroic layers (10cm - 2m) formed of discrete bodies appear



PLATE 2-9: Rapakivi potassium feldspars concentrated at the contact of the large single-feldspar granite inclusion from Plate 2-8.
Toothpick for scale.



PLATE 2-10: Unusual mafic inclusions near two-feldspar/single-feldspar transition. Note that the margin next to left foot is chilled, while the margin next to the right foot is not. American Express card for scale.
'F' on stratigraphic column (Figure 2-2).

at irregular intervals within the more felsic layers. These isolated pockets of mafic rock have been dubbed "pillows" because of their resemblance (and genetic similarities) to sub-aqueous pillow lavas (Plate 2-11). The pillows have soft, lobate-cusate contacts with the enclosing unit, surrounded by a fine-grained, chill rind 1-3cm thick, enriched in the hydrous, mafic phases biotite and amphibole. Pillows grade inward to coarser gabbro with a higher plagioclase content, still with dominant amphibole and rare, stubby green pyroxene. Potassium feldspar xenocrysts found within the pillows have plagioclase mantles, and one layer of gabbroic pillows contains elongate quartz inclusions rimmed by feldspar in linear concentrations parallel to the dominant layering.

Felsic material underlying the gabbroic layers commonly intrudes upward, perpendicular to the layering, through the chilled margin of the gabbroic pillows forming felsic diapirs which become wispy and diffuse higher in the gabbroic layer. The resultant contact resembles ball and flame, or load cast, structures like those seen in sedimentary layers (Plate 2-12). Coarser assemblages of quartz and feldspar commonly occur in felsic units near contacts with gabbroic layers. Hydrous, mafic phases are also found concentrated in the underlying felsics, almost universally displaying a distinct flow lamination parallel to the contact (Plate 2-13).

One large, gabbroic layer (mentioned above) exhibits only a basal chill with the underlying granitic unit, while the upper portion of the layer grades to a heterogeneous, coarse "diorite" within three meters. The basal contact is cusate, finer-grained, and enriched in amphibole and biotite. A thin (2-10cm) layer of intermediate to felsic material sits sandwiched between the underlying granite and overlying gabbro, tabular biotite and prismatic amphibole distinctly foliated parallel to the contact. Large, diapiric upwellings



PLATE 2-11: Discreet mafic pillows showing cuscate-lobate contacts with surrounding intermediate matrix. Pen for scale.



PLATE 2-12: Diapir of felsic material into overlying gabbroic layer. Small shell (2 cm) near center of picture for scale.
'G' on stratigraphic column (Figure 2-2).



PLATE 2-13: Flow lamination in underlying intermediate unit parallel to the contact. Dashed line shows lamination orientation. Knife for scale.



PLATE 2-14: Large granitic layer underlying large gabbroic layer. Note the load cast type structures in the gabbroic layer and the diapirs in the granitic layer. Lens cap in center of picture for scale. 'H' on strat column (Fig. 2-2).

of this material intrude as much as one meter into the overlying gabbro before becoming disaggregated and faint.

Granitic Layer

Only one layer had the field name "granite," although point counts of some of the layers called "diorite" revealed them to be granites. The field "granite" proved to be the most felsic unit of the layered sequence and contains large quartz and kspars crystals. It lies directly below the largest gabbroic layer, forming the cusped/lobate contact described above (Plate 2-14). Abundant fine-grained, gabbroic enclaves ranging from 0.3 to 4 cm in diameter, modally and texturally similar to those found throughout the CMIC, are concentrated near the contact (Plate 2-15).

Ovoid pods of granite appear in the northernmost intermediate units of the layered series, long axes ranging from 1 cm to 0.5 meter (Plates 2-16, 2-17). From relationships observed elsewhere in the layered gabbro-diorite unit, these ovals are apparently cross-sections of granitic pipes. Pipes observed outside Sommes Cove appear to be long, continuous diapirs. Orientations of these pipes are perpendicular to layering, as are diapirs.

Late-stage Dikes

Three compositions of late stage intrusions -- basaltic, pegmatitic/aplitic, and composite dikes -- provide a convenient contrast with the units of the layered sequence. Characterized by sharp, distinct contacts and angular xenoliths, the cross-cutting basaltic and aplitic dikes exhibit no comagmatic interaction with the surrounding country rocks. Seven basaltic dikes, all trending roughly N10W, vary in width from 0.5 to 1.5 meters. Their contacts provide the finest-grained rocks in the field area, obviously chilled

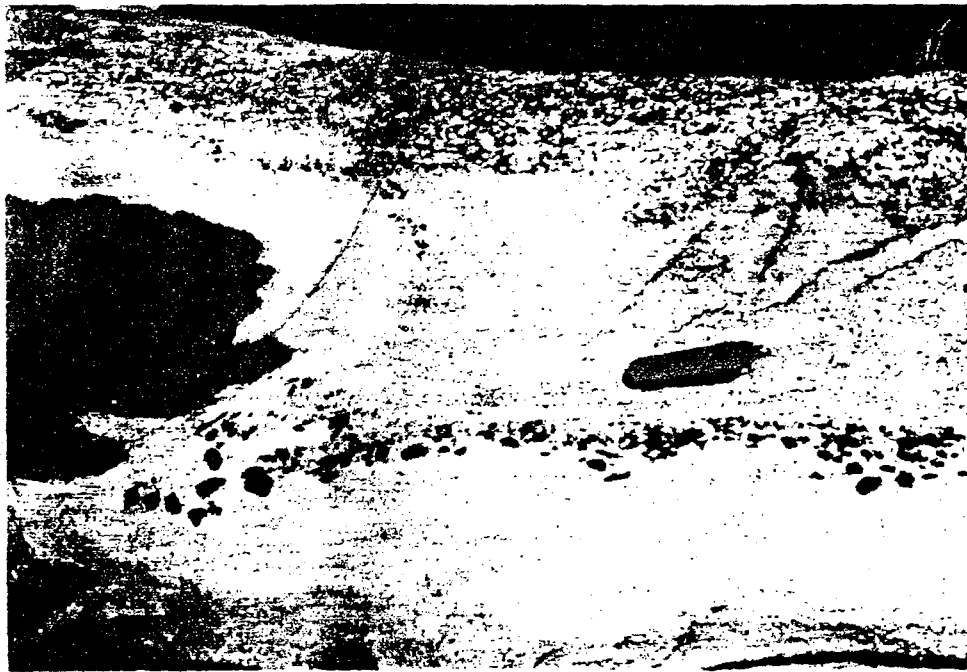


PLATE 2-15: Enclaves similar to those found higher in CMIC. This picture was taken in an area adjacent to Sommes Cove. Knife for scale.



PLATE 2-16: Ovoid pipe cross-sections in an intermediate unit. During high tide, these outcrops form beautiful, glaciated "whale backs." Human for scale. 'T' on stratigraphic column (Figure 2-2).



PLATE 2-17: Cross-section of a quartz and kspars pipe.
Swiss army knife tweezers for scale. 'T' on stratigraphic column (Figure 2-2).



PLATE 2-18: Composite dike of disaggregate mafic pillows in aplite matrix.
Finger for scale. 'T' on stratigraphic column (Figure 2-2).

against the cold, solidified country rocks of the layered sequence. Some pegmatite dikes, and closely associated aplites, are en echelon and contain very few mafic minerals. The trend on these dikes was difficult to ascertain, though they strike roughly perpendicular to the basaltic dikes. One angular xenolith of the surrounding quartz monzodiorite is visible in a large pegmatite dike.

A composite sill low in the section, also with sharp lateral contacts, displays strikingly similar mingling textures as its host rocks. An aplitic matrix of quartz, ksp, plagioclase, and small biotite flakes surrounds dramatically chilled mafic pillows, finer than any gabbro within the layered series (Plate 2-18). This dike's orientation, exactly parallel to the country rock's layering, coupled with the nature of its contacts indicates that although it intruded after the layered sequence was well developed, it still followed planes of weakness between the layers. This dates the composite sill after the layered units and before the basaltic and aplitic dikes.

CHAPTER THREE

PETROGRAPHY

SAMPLING STRATEGY

Thirty five samples, collected for petrographic and geochemical analyses, represent all major units recognized. Five samples of chilled gabbro/ "diorite" contacts, including one from the composite dike, provided excellent thin sections for comparison of different mafic-felsic interactions. Basaltic and pegmatitic dike samples reveal important petrogenetic relationships with units within the layered series, or with other units in the CMIC. Many samples of the two major "dioritic" sections helped unravel the crystallization history of these hybrid units. The major granitic unit was also sampled, in hopes of discovering its relationship to the Cadillac Mountain Granite and the likelihood of its being a relatively uncontaminated host liquid end member.

During the last week of the Keck project, I prepared thirty-two thin section blanks at Williams College, and sent them for preparation to Spectrum Petrographics, Inc. in Utah. All units displayed in Sommes Cove have at least one equivalent thin section, while the most important units, such as the granite, the chilled gabbro, and several "diorites," have as many as three. Analysis was made using Leitz binocular petrographic microscopes. The five classifications used during field work apply equally well to the petrographic analysis.

ROCK UNITS

Basalt

This unit, represented by three of the late-stage mafic dikes, displays remarkable homogeneity. Randomly-oriented plagioclase laths are strongly zoned and/or twinned, many showing calcite and opaque alteration (Plate 3-1). Plagioclase sizes range from groundmass to 4 mm long, while most laths are approximately 0.25 - 0.75 mm. By the Michele - Levy method, their composition is labradorite (An₅₉). Ophitic clinopyroxene is the dominant mafic mineral, with early formed (euhedral and not ophitic), relict olivines uncommon. Amphibole is sparse, and sphene and apatite are rare accessories. The dike margins are extremely fine grained, also with a plagioclase and clinopyroxene groundmass. Euhedral olivines, 0.05-0.2 mm, are common. Although mentioned in the literature, no felsic xenocrysts have been observed, either in these slides or in the field.

Aplite/pegmatite

These units contain felsic mineral assemblages; quartz, microcline, and orthoclase dominate, with approximately 2% biotite as the only mafic phase (Plate 3-2). Large orthoperthite crystals are anhedral and embayed, indicating resorption. Amphibole, the most common mafic in all other felsic units, is conspicuously absent. Biotite is primarily recognized by its weathering product serpentinite. Apatite needles, though less than 1%, are common. Textures are equigranular, approximately 0.5 mm.

Gabbro

Gabbros typically consist of randomly oriented plagioclase laths, 0.05-0.75 mm, contained within ophitic hornblende, identified by its green/tan



PLATE 3-1: Basaltic dike with large plagioclase phenocryst.
Crossed polars. Field of view = 3mm.

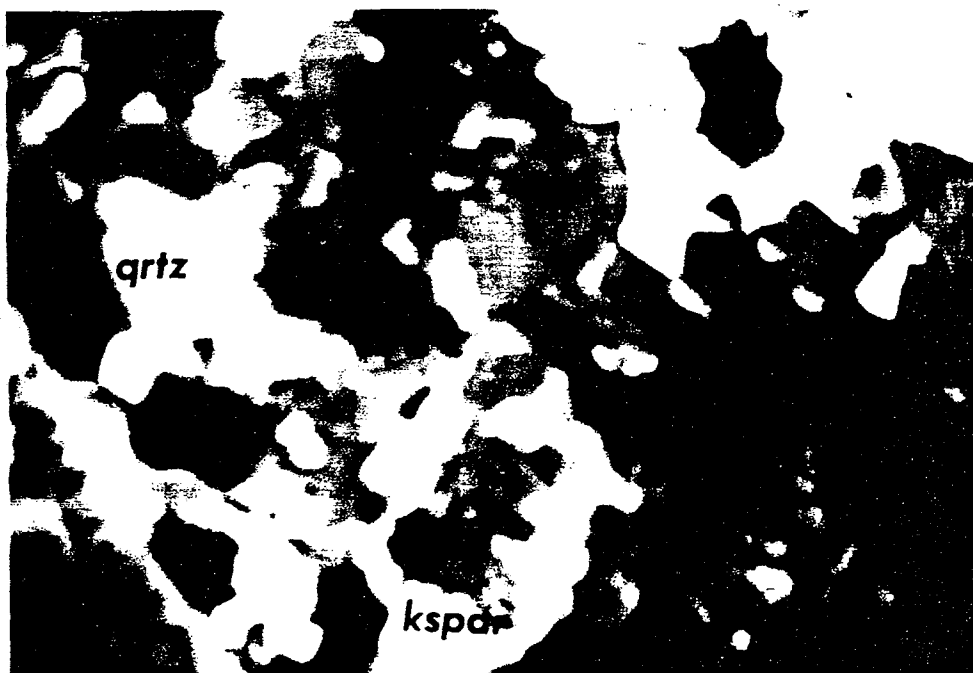


PLATE 3-2: Aplite with quartz and potassium feldspar.
Crossed polars. Field of view=3mm.

pleochroism (Plate 3-3). Plagioclase commonly exhibits strong zoning with complex reversal patterns; Michele-Levy reveals compositions from An₃₂₋₆₃. More anorthite-rich plagioclase dominates the chilled gabbros, while the less anorthitic plag is found in coarser gabbros. While some amphibole may be primary, the majority appears secondary with obvious to very faint relict clinopyroxene cores, particularly within those amphiboles most altered (Plate 3-4). Hornblendes are up to 0.5 mm in diameter. Magnetite-ilmenite is ubiquitous, commonly found in association with epidote and biotite, an alteration of hornblende. Apatite is common throughout the layered sequence, while anhedral zircons and sphene are less common.

Coarse gabbros, with touching, hypidiomorphic crystals, display cumulate texture (Plate 3-5). Plagioclase crystals commonly indicate resorption, with corroded and embayed faces, suggesting disequilibrium conditions. Potassium feldspar xenocrysts, present at least as far as two meters from the nearest felsic unit, are mantled by plagioclase (rapakivi texture).

Felsic/Gabbro Contacts

Perhaps the most interesting slides are of contacts between gabbroic and more felsic units (felsic units discussed below). These chilled gabbros are variably aphanitic, reflecting the compositional (and most likely, thermal) contrast with the contacting "diorite" or granite (Plates 3-6 and 3-7). For example, the gabbro in contact with the granite is much finer grained, with biotite crystals between 0.1 and 0.25 mm long, than the rims of the gabbro pillows contained within a quartz monzodiorite matrix. Plagioclase in both is randomly oriented and twinned. Biotite enrichment at the contact is striking, the tabular crystals exhibiting flow lamination parallel to the contact (Plate 3-8). Hornblende, up to 0.25 mm long, within the 2 mm thick biotite

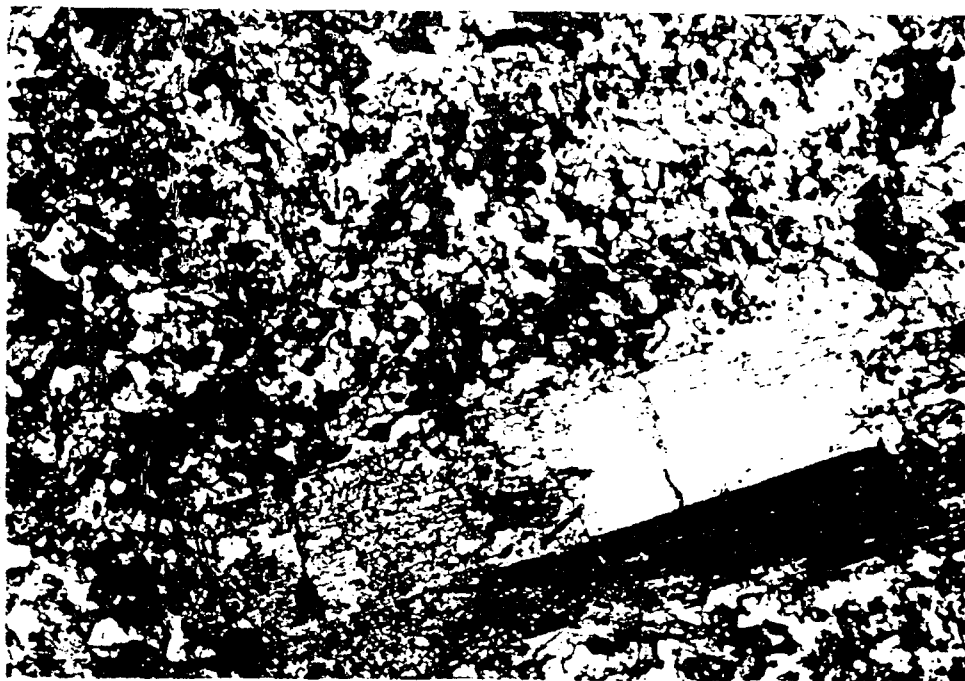


PLATE 3-3: Chilled gabbro with partially calcitized plagioclase phenocryst.
Crossed polars. Field of view = 3mm.
'A' on stratigraphic column (Figure 2-2).

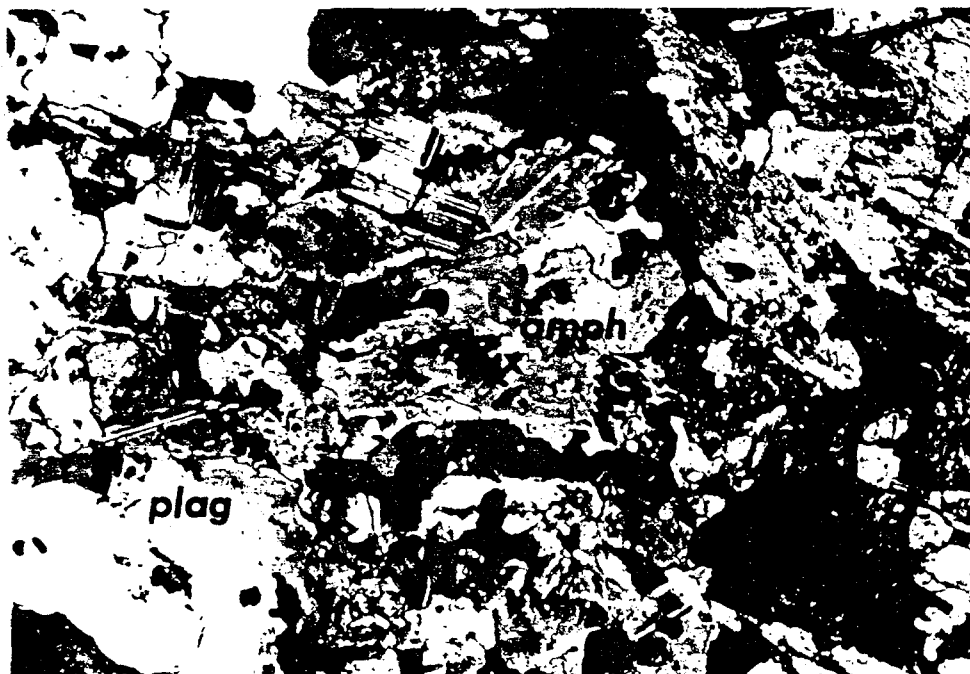


PLATE 3-4: Coarse gabbro, with complex texture and many different grain sizes. Note the amphibole with a pyroxene core near the center of the view.
Crossed polars. Field of view=3mm.

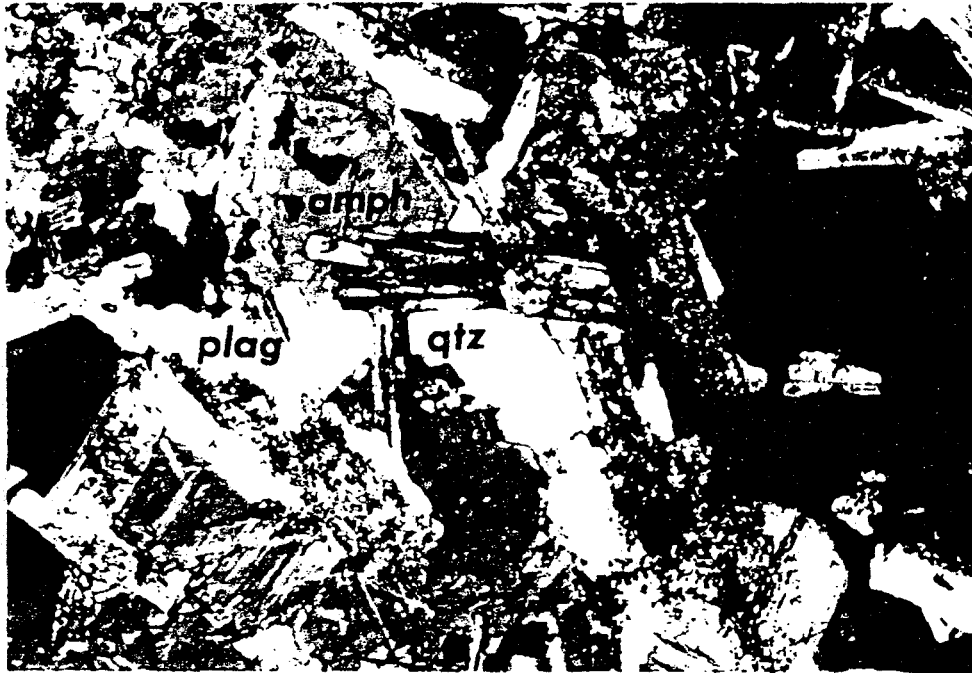


PLATE 3-5: Cumulate coarse gabbro of touching plagioclase and amphibole crystals, and interstitial quartz.
Crossed polars. Field of view = 3mm.

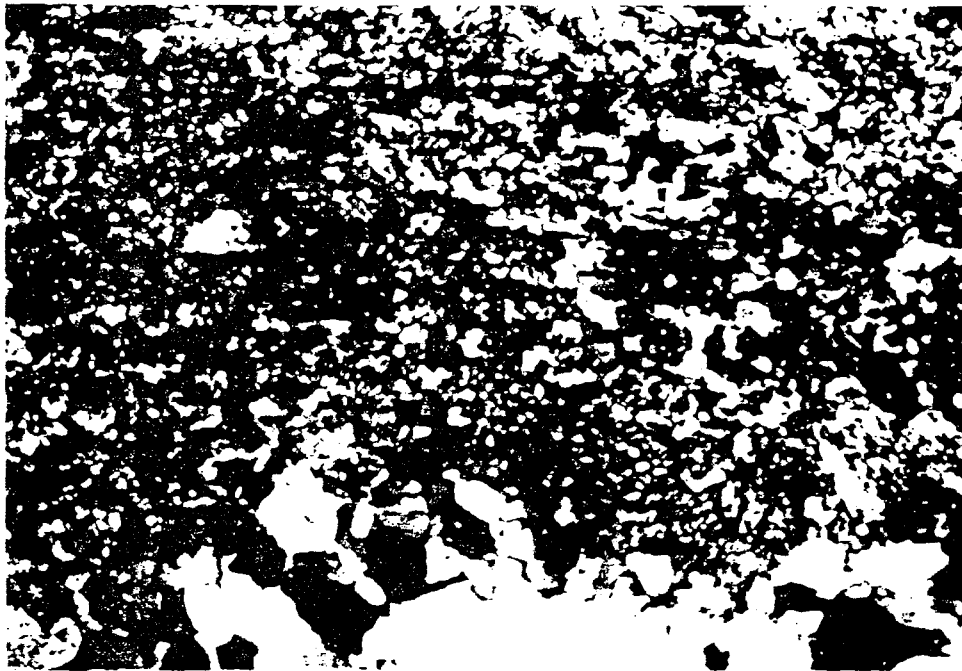


PLATE 3-6: Chilled contact against felsic matrix. Compare grainsize with plate below. Crossed polars. Field of view = 3mm.
'H' on stratigraphic column (Figure 2-2).



PLATE 3-7: Chilled margin against quartz monzonite matrix. Mafic minerals are much coarser than above. Crossed polars. Field of view=3mm.



PLATE 3-8: Lamination in chilled margin of elongate biotite and hornblende parallel to the contact. Dashed line shows lamination direction. Uncrossed polars. Field of view = 3mm. 'H' on stratigraphic column (Figure 2-2).

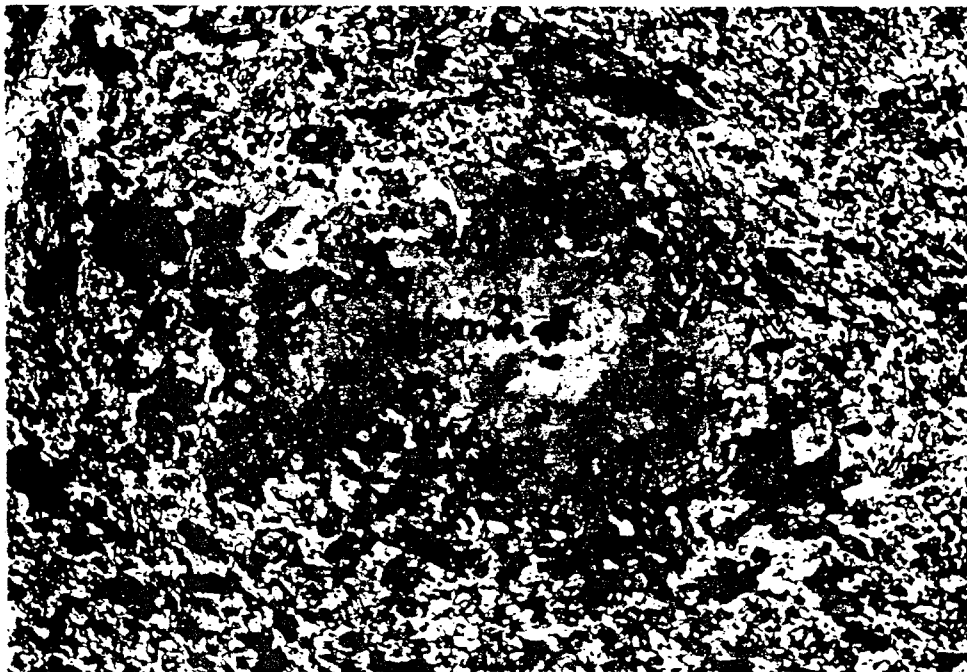


PLATE 3-9: Glom of secondary amphiboles "wrapped" by elongate biotite and hornblende. Uncrossed polars. Field of view=3mm.

enrichment zone also shows flow lamination. Chill contacts with larger grains (0.75 mm), such as those in pillows contained in a less felsic matrix, do not exhibit as strong a flow lamination. Glomero-porphyrific clots exist at many contacts, commonly of secondary amphibole, some with faint clinopyroxene cores. In one contact, the biotite and elongate hornblendes "wrap" around a glom, consistent with the observed flow texture (Plate 3-9). Apatite is common, and one contact has unusually large sphene crystals, 0.5 mm, sandwiched between the two units.

Some mechanical mixing is evidenced at the contacts; quartz and kspars xenocrysts and gloms exist in the mafic unit (Plate 3-10), and small mafic clots of hornblende and plagioclase reside within the felsic unit. Though no enclaves were sampled, the observed mafic clots display enclave textures described in the literature (SEAMAN and RAMSEY, 1992).

"Diorite"

Many of the collected samples had been loosely dubbed "diorite" while in the field. Petrographic analysis revealed that in fact this group represents a relatively broad range of intermediate to felsic rocks. Quartz is found in almost all intermediate samples, ranging in mode from just under 5% to 25%. Plagioclase is ubiquitous with strong normal zoning, commonly with embayed, partially-resorbed crystals. Plagioclase compositions in these units are albite-rich, Michele-Levy indicating compositions of $An_{<39}$. Common potassium feldspars include orthoclase, microcline, and perthite. Hornblende is the dominant mafic phase, though biotite, some with zircon pleochroic halos, is also prevalent. Pyroxenes usually have thick amphibole reaction rims (Plate 3-11). Apatite needles are ubiquitous; anhedral to euhedral zircon and subhedral sphene are less common. Opaque concentrations vary from



PLATE 3-10: Felsic glom of biotite and quartz within chilled margin.
Crossed polars. Field of view = 3mm.



PLATE 3-11: Intermediate unit displaying pyroxenes with thick amphibole
reaction rims. Calcic plag is rimmed by alkali feldspar.
Crossed polars. Field of view=3mm. 'B' on strat column (Fig. 2-2).

TABLE 4-1

SOMMES COVE - Major and trace element chemistry

Sample #	FJV-1a	FJV-8	FJV-14	FJV-21	FJV-4	FJV-5	FJV-23	FJV-27	FJV-3	FJV-6	FJV-7	FJV-15	
Type	Basalt Dike	Coarse Gab	Composite Dike	Basalt Pillow	Chill Transition	Di	Diorite	Diorite	Diorite	Transition Gr	Granite	Intermed Gr	Composite Aplite
Method	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	
SiO2	47.67	54.69	54.12	50.38	63.64	63.54	54.57	47.23	72.64	71.74	66.89	72.20	
TiO2	1.30	1.83	0.51	2.54	0.63	0.71	2.09	1.82	0.34	0.36	0.52	0.29	
Al2O3	15.12	14.63	15.17	14.60	13.78	14.41	14.61	16.15	12.80	12.96	13.75	13.73	
Fe2O3	1.12	1.13	0.73	1.52	1.69	1.94	1.52	1.49	0.85	0.98	1.24	0.68	
FeO	7.49	7.56	4.88	10.17	3.38	3.89	10.16	9.94	1.63	1.96	2.47	1.36	
MnO	0.16	0.15	0.09	0.26	0.09	0.09	0.17	0.21	0.09	0.12	0.12	0.08	
MgO	7.99	4.30	7.02	5.04	2.41	2.68	3.93	7.46	0.28	0.25	1.90	0.31	
CaO	10.23	7.08	7.21	7.67	3.76	4.27	7.08	8.42	0.99	1.06	3.03	1.56	
Na2O	1.83	2.70	7.40	2.77	3.19	3.37	2.80	2.69	2.43	2.93	3.28	2.80	
K2O	0.58	1.50	1.64	1.03	2.94	2.75	1.68	0.96	4.89	4.60	1.56	4.18	
P2O5	0.18	0.32	0.13	0.41	0.12	0.14	0.28	0.28	0.03	0.02	0.07	0.04	
LOI	1.85	1.62	1.10	1.88	1.26	1.22	0.67	3.33	0.46	0.52	0.95	0.55	
TOTAL	95.51	97.51	100.00	98.27	96.89	99.01	99.56	99.98	97.42	97.50	95.77	97.78	
Ni	24	0	140	0	17	42	0	68	0	25	21	25	
Cr	532.0	113.0	150.0	176.0	112.0	148.0	51.0	207.0	15.0	75.0	101.0	3.0	
V	174.0	140.0	60.0	201.0	52.0	42.0	168.0	109.0	0.0	7.0	33.0	0.0	
Sc													
Co	29.0	27.0	32.0	25.0	12.0	15.0	27.0	38.0	6.0	0.0	17.0	5.0	
Cu													
Zn	72	36	100	33.2	50	50	78	184	38	90	208	51	
Ga													
Cs													
Ba													
Rb	0	47	57	0	79	79	35	10	124	106	73	158	
Th													
Sr	222	262	205	253	203	215	243	264	95	60	177	117	
Zr	135	228	116	244	235	263	228	169	362	478	241	269	
Nb	9	15	8	17	22	17	16	14	13	27	12	15	
Hf													
Ta													
La													
Ce													
Nd													
Sm													
Eu													
Tb													
Yb													
Lu													
Y	14.0	37.0	21.0	32.0	61.0	38.0	40.0	22.0	41.0	77.0	33.0	54.0	
Sb													
U													
Be													

HUTCHISON WEATHERING INDEX:

WI= 70.6935 68.038 120.4305 68.31 70.8384 72.9982 69.407 75.6628 67.2818 69.512 56.6284 66.2112

sample to sample, frequently in association with weathered amphibole and biotite.

The most felsic "diorite" collected, FJV-4, is actually a two-feldspar granite (mentioned in the previous chapter), with equal proportions of quartz, plagioclase, and alkali feldspar. It lies directly below the "transition" to granite shown in Figure 2-2, and contains biotites surrounded by amphibole. The most mafic sample, FJV-27, is a true petrographic diorite, and occurs high in the layered sequence. See Table 3-1 for point counts.

The "diorite" units display abundant textures suggestive of hybridization. The textures are typically "patchy," with mafic and felsic clots several millimeters across (Plates 3-12 and 3-13). Mafic clots consist of amphibole, biotite, and plagioclase. Felsic clots consist of equant, euhedral sodic plagioclase, quartz, and euhedral kspar. Large, equant orthoclase, 3-5 mm across, commonly surrounds hypidiomorphic, 0.2-0.3 mm plagioclase, rare pyroxene, amphibole, and biotite. Some plagioclase crystals contain cores of alkali feldspar, and vice-versa. Feldspars frequently are partially resorbed and/or replaced.

Granite

The large granite layer is represented by three samples: FJV-3, FJV-6, and FJV-7. The former represents the first appearance of plagioclase-poor granite, just above the transition from the two feldspar granite (Plate 3-14). Quartz is almost 40% of this rock, while plagioclase has dropped to less than 5%. Mosaics of potassium feldspar are comprised of small, euhedral grains. Primary biotite, mode less than 2%, is serpentized, while secondary biotite from amphibole shows a more reddish color in plane light. Apatite and euhedral zircon are common, and ilmeno-magnetite is less than 1%.

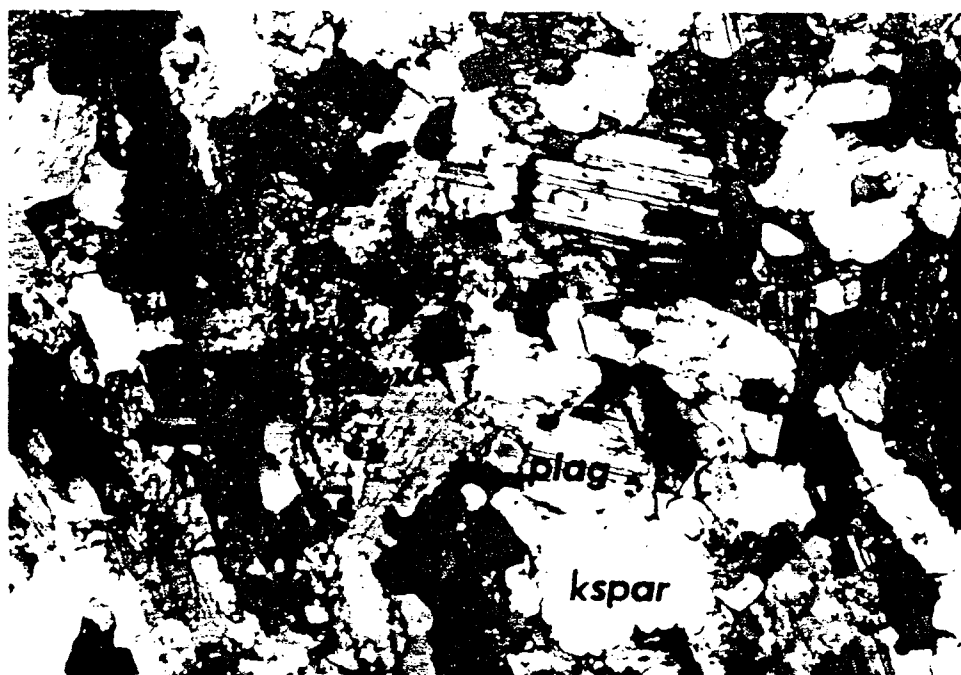


PLATE 3-12: Intermediate unit composed of felsic and mafic gloms.
Crossed polars. Field of view = 3mm.
'B' on stratigraphic column (Figure 2-2).

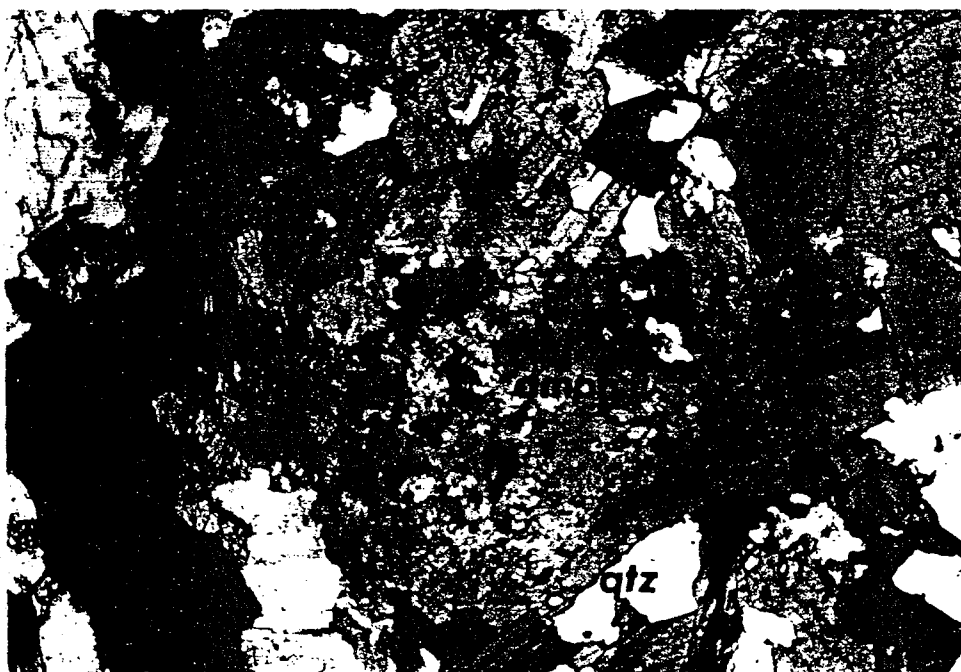


PLATE 3-13: Large mafic clot within hybridized unit.
Uncrossed polars. Field of view=3mm.



PLATE 3-14: FJV-3, single-feldspar granite.
Crossed polars. Field of view = 3mm.
'C' on stratigraphic column (Figure 2-2).



PLATE 3-15: Granitic unit, FJV-6, with amphibole crystal.
Crossed polars. Field of view=3mm.
'C' on stratigraphic column (Figure 2-2).

FJV-6 represents the largest outcrop of granite (Plate 3-15), while FJV-7 is the thin, intermediate layer between it and the overlying mafic chill (Figure 2-2). Quartz, microcline, and perthite are common; in the former, the plagioclase content is around 5%. Hornblende is the dominant mafic mineral, and most biotite appears secondary (replacing amphibole), closely associated with opaques and secondary epidote. Some kspar mosaics are also seen here, with inclusions of altered biotite. Apatite is seen, though zircon is absent. The plagioclase content jumps to ~20% in FJV-7; plagioclase crystals are strongly zoned and resorbed. Biotite dominates; amphibole is rare. Corroded zircon is seen with apatite as accessories.

Sample #	Quartz	Kspar	Plag	Pyroxene	Amphibole	Biotite	Opakes	Accessories	Total Pts
FJV-1a	0.00%	0.00%	44.67%	46.26%	0.00%	0.00%	8.08%	1.00%	1003
FJV-3	33.99%	54.61%	2.78%	0.00%	0.00%	5.45%	1.59%	1.59%	1009
FJV-4	24.90%	24.30%	26.40%	1.10%	13.70%	7.50%	0.60%	1.50%	1000
FJV-6	35.71%	54.70%	1.29%	0.00%	2.77%	2.47%	1.38%	1.68%	1011
FJV-8	4.30%	0.40%	30.90%	8.80%	28.30%	18.70%	6.50%	2.10%	1000
FJV-23	5.08%	28.71%	26.62%	5.68%	23.03%	5.88%	3.99%	1.00%	1003
FJV-27	0.00%	5.18%	37.09%	5.08%	34.90%	7.98%	8.08%	1.69%	1003

TABLE 3-1 Point Counts: 1a=Basalt Dike; 3, 6=Granite; 4=Two Feldspar Granite; 8=Coarse Gabbro; 23, 27=Heterogeneous "Diorite"

CHAPTER FOUR

GEOCHEMISTRY

Twelve representative samples were selected for major-element and trace-element analysis. Four samples from each of the three major silica ranges were selected: four basalts and gabbros, four intermediate units, and four granites and aplites.

METHODOLOGY

Sample Preparation

Reduction of selected samples of adequate size to a fine powder and then fusion into a glass disc for XRF analysis involved several steps. Each sample's weathering rind (2 mm to 2.5 cm) was removed using the water lubricated rock saws at Fort Lewis College in Durango, Colorado. To ensure representative chemical results, a core rock at least 20 times the size of the largest crystal was preserved. However, the next stage (coarse crushing) could only accept samples up to 7 cm in diameter. Large rock samples, therefore, were cut into several pieces to satisfy both of these requirements. Ultrasonic cleansing of sawed samples was unnecessary because only non-contaminating saws were used, i.e. water lubricated vs. oil lubricated. Colorado College uses oil lubrication for their rock saws, so rocks sawn there for geochemical analysis must be ultrasonically cleansed.

A large jaw crusher, located at Colorado College, reduced the samples to chips approximately 2x3 cm. Before each sample, the jaw crusher was cleaned of large chips and powder from preceding samples with a brush, then precontaminated with a small portion of the sample to be reduced and cleaned again. This ensured samples with as little contamination as possible.

Reducing samples to powder from this stage proved extremely difficult using just the Colorado College facilities, as inadequate machinery exists at the college to easily reduce the chips from the jaw crusher to a size appropriate for the shatterbox. I attempted several techniques, including use of a hydraulic core splitter and a mortar and pestle to further crush samples; these proved to be unsatisfactorily slow. I therefore went to the United States Geological Survey (USGS) located at the Federal Center in Lakewood, Colorado. The labs at the USGS are well equipped for geochemical preparation, where a ceramic plate grinder produced 100 grams of powder from each of the twelve samples in four hours. Contamination of samples was avoided by cleansing the grinder with pure quartz sand and precontamination between each sample. The powders produced by this machine were sufficiently fine (100% 80-mesh/80% 100-mesh) to ensure random distribution of elements, so use of the shatterbox was unnecessary.

These powders were fused into discs for XRF analysis. Ten grams of each sample were dried overnight in an oven at 115° centigrade to ensure accurate weight measurements. One ± 0.0005 gram of powder was mixed with nine ± 0.0005 grams of lithium tetraborate flux and placed in a clean platinum crucible. Less than 0.1 gram of ammonium nitrate was added to ensure complete oxidation of iron and prevent reaction between powders and the platinum crucible.

Chemoline gas and compressed air, mixed in a bunsen burner, heated the mixture in the crucible until it glowed a bright orange to approximately 1200° centigrade, and melted its contents. The melt was thoroughly mixed by an orbit shaker, on which the entire crucible-burner system was placed. While the powder melted and mixed, a mold for the disc was heated over a separate

burner until it glowed a dull red. When the melt was completely mixed, after 20-30 minutes, the bunsen burners were shut off, the crucible was grasped by platinum tongs, and the mixture was poured into the hot mold. Although the aim is to cool the disc rapidly enough to encourage the glass to solidify without crystalizing, too rapid a cooling rate will fracture the disc. Therefore, the disc cooled in the mold until a popping noise due to the disc separating from mold was heard, and then completed cooling on a hot plate heated to 150° centigrade. The platinum crucible and mold were cleaned between samples in a dilute hydrochloric acid bath.

X-ray Fluorescence Spectrometry (XRF)

A Rigaku 3070 x-ray fluorescence spectrometer with a rhodium target x-ray tube analyzed the glass discs. X-rays from the rhodium tube bombard the disc and remove inner-shell electrons within the various elements to higher energy orbitals. As the outer-shell electrons cascade down to fill the inner-shell vacancies, they must lose energy and emit x-rays of diagnostic wavelength and frequency. Two different detectors receive the emitted radiation. A solid state electronic detector detects the higher energy radiation emitted by heavier major and all trace elements. This detector is resistant to drift; its calibrations, therefore, remain accurate for weeks. The other detector is more sensitive; it uses a mixture of P-10 gas and helium, and detects the lower energy radiation emitted by lighter elements. Because of the variability of gasses and pressure, this detector is more subject to drift. Therefore, when the gas tank was changed, the machine's calibration curves were checked against known standards for the lighter major elements. Also, the accuracy of both detectors was checked every analysis by comparing calculated data with known standards, details of which are discussed in the results section below.

Loss On Ignition (LOI)

During melting in the manufacture of XRF discs, a certain weight percentage of sample is lost from evaporation of volatiles - water, carbon dioxide, sulfur, chlorine, and fluorine. The final chemical data reflect this lost mass in the total weight percent calculations. This lost mass was measured for each sample, thereby bringing weight totals up to more accurate values. One gram of each powder, $\pm 0.0005\text{g}$, placed in a pre-weighed ceramic crucible was heated in a muffle furnace to 900° - 1000° centigrade for four hours. After cooling in a dessicator, each sample, still within the crucible, was reweighed to attain the initial loss. Initial % LOI was calculated from initial loss with the following equation:

$$(INITIAL\ LOSS \div INITIAL\ WEIGHT) \times 100 = INITIAL\% LOI$$

The final % LOI value must consider the weight added by the oxidation of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}) during the heating of the crucible. The following equation yields the final % LOI value:

$$\% LOI = INITIAL\ LOI + (0.111348 \times wt\% FeO)$$

These values adjust the total weight percents, as seen in Table 4-1.

XRF RESULTS

Several techniques provide indication of the validity of the geochemical results. Both the quality of the rock sample and the quality of analysis can be quantified.

Rock Sample Quality - Weathering Index (WI)

In an attempt to quantify the degree of weathering of each sample, a weathering index was calculated from the results of the XRF analysis. The equation (from HUTCHISON (1974))

$$WI = \{ [(0.092) Na_2O] + [(0.028) MgO] + [(0.085) K_2O] + [(0.026) CaO] \} \times 100$$

provides a value that gives an indication of sample freshness. The coefficient for each oxide represents the cation atomic percentage over its atomic weight divided by the oxide's bond strength. Oxides are in weight percent. Higher WI's indicate fresher samples; completely fresh granites and basalts may have values of 80 and 90 respectively. Weathered granites and basalts have WI's in the 30's and 20's.

Sommes Cove samples have WI's from 56 to 120, with most values in the high 60's to low 70's range. The lower values indicate moderately fresh samples, while the WI's in the 70's suggest fresher samples. The one WI of 120 for FJV-14 results from the anomalously high sodium oxide value, possibly due to excessive handling of the XRF disc or some other contamination. Overall, the values indicate moderately fresh samples.

Analysis Quality - Accuracy of XRF results

Accuracy of the analytical technique, a measure of how close to "true" the measured values are, is attained by comparing measured oxide and trace element values to known, published values. Known standards of similar composition to the Sommes Cove samples were run with each analysis; e.g. a known basaltic standard was run with the Sommes Cove basalts and gabbros and a granitic standard was run with the most felsic disc. The standard's measured values compared with the actual, published values provide a measure of error

ACCURACY OF XRF ANALYTICAL RESULTS

Basalts-BCR-1	Measured	Actual	% Error	Granites-NIMG	Measured	Actual	% Error	"Diorites"-GSP-1	Measured	Actual	% Error
SiO2	52.663	54.350	3.18%	SiO2	74.377	75.700	1.78%	SiO2	65.492	67.370	2.70%
TiO2	2.126	2.220	4.23%	TiO2	0.109	0.090	21.11%	TiO2	0.635	0.656	3.20%
Al2O3	14.029	13.630	2.91%	Al2O3	11.867	12.080	1.76%	Al2O3	14.959	15.160	1.33%
FeTOTAL	13.152	13.460	2.29%	FeTOTAL	1.920	2.020	4.95%	FeTOTAL	3.734	4.320	13.56%
MnO	0.175	0.182	3.85%	MnO	0.015	0.021	28.57%	MnO	0.037	0.040	7.50%
MgO	3.189	3.450	7.57%	MgO	0.078	0.060	30.00%	MgO	0.977	0.990	1.31%
CaO	6.603	6.950	4.99%	CaO	0.984	0.780	26.15%	CaO	2.060	2.040	0.98%
Na2O	4.132	3.270	26.36%	Na2O	3.843	3.360	14.38%	Na2O	4.259	2.800	52.11%
K2O	1.725	1.690	2.07%	K2O	4.709	4.990	5.63%	K2O	5.224	5.510	5.19%
P2O5	0.308	0.370	16.76%	P2O5	0.025	0.010	150.00%	P2O5	0.256	0.280	8.57%

TRACE ELEMENTS in PPM

Ni	7	13	46.15%	Ni	18	8	125.00%
Cr	16	16	0.00%	Cr	1	12	91.67%
V	261	401	34.91%	V	13	2	550.00%
Co	31	36	13.89%	Co	5	4	25.00%
Zn	320	129	148.06%	Zn	58	50	16.00%
Rb	19	47	59.57%	Rb	409	320	27.81%
Sr	316	330	4.24%	Sr	1	10	90.00%
Nb	20	14	42.86%	Nb	74	53	39.62%
Y	27	39	30.77%	Y	194	143	35.66%

TABLE 4-2: Accuracy of XRF results for the three groups. Standards used are shown in the upper left corner of each table, next to group name. For example, the basalt standard is BCR-1. Shaded error values are within acceptable limits.

$$\% \text{ error} = |[(\text{Measured}-\text{Actual})/\text{Actual}] \times 100|$$

As shown by Table 4-2, many measured values are not within acceptable accuracy limits.

Compensation for High Error Values

To compensate for measured values with greater than 5% error, a manual correction was performed. Each oxide (or trace element) emits x-ray radiation of a diagnostic frequency, and the higher percentage (or ppm) of an element, the more intense the measured peak of its given frequency will be. The XRF uses different straight line calibration curves for each element to convert measured peak intensities to weight percentages (or ppm). These lines are determined by running known standards and setting the curves to match the publish data. Each calibration line has a slope and an axis intercept; the slope indicates how peak intensity changes with increased concentration, while the intercept sets the range of values used for the element measured. However, the detectors within the machine are highly sensitive and subject to drift; factors such as room temperature, internal temperature, P-10 and helium gas pressure, and time can all affect what the detectors measure. As a result, the calibrated lines will no longer correctly correspond to measured peak intensities. For example, the granites show a 30% error in measurement of magnesium oxide; this must result from either incorrect line slope or incorrect axis intercept. If one can determine which is incorrect, the value can be appropriately adjusted and the line manually recalibrated.

Low values for weight percent (or ppm) are most dramatically affected by the intercept, as the peak intensities are low and fall near the axis. Higher

intensity peaks are more dependent on the slope of the calibration line to accurately convert them to weight percent (or ppm). The magnesium oxide value for the granites are relatively low - 0.078 for the standard - and therefore most affected by the calibration line's axis intercept. By subtracting 0.018 from the measured value, the line is effectively lowered and recalibrated to match the published figure of 0.060; this same correction, subtracting 0.018 wt%, was performed for all MgO values for each granite sample. If high error was determined as the result of incorrect slope, the slope of the calibration line was adjusted. Major and trace element values for all samples with high error were adjusted according to these principles. Theoretically, this reduced analytical error for all elements; the values used for all geochemical plots, and listed in Table 4-1, were adjusted in this way. Unadjusted values are in the Appendix.

FeO and Fe₂O₃ Values

XRF analysis cannot distinguish between the two different oxidation states of iron, so the weight percent returned for iron oxide is a value for total iron. To separate the two, ratios based on typical basaltic and granitic rocks were used. For all samples with less than 60 wt% silica, the assumed ratio for Fe₂O₃/FeO was 0.15. For all samples greater than 60 wt% silica, the assumed ratio for Fe₂O₃/FeO was 0.5. Considering molecular weights, these assumptions yield the following basaltic equations,

$$Fe_2O_3 = Total\ Fe / (1 + 1.111031 / .15) = Total\ Fe / 8.41$$

$$FeO = Total\ Fe / (1.111031 + .15) = Total\ Fe / 1.26,$$

and granitic equations,

$$Fe_2O_3 = Total\ Fe / (1 + 1.111031 / .5) = Total\ Fe / 3.22$$

$$FeO = Total\ Fe / (1.111031 + .5) = Total\ Fe / 1.61.$$

General Chemistry of Sommes Cove Units

The major- and trace-element chemistries of all analyzed units are shown in Table 4-1. Silica values fall in the range of 47.23 to 72.64 wt%, thus representing the compositions expected from field observations: gabbro through granite. Although the major oxides behave somewhat erratically as compared to silica, most have simple linear trends on Harker diagrams (Figures 4-2 through 4-6). The oxides Al_2O_3 , MgO , FeO , Fe_2O_3 , TiO_2 , P_2O_5 and CaO all display negative correlations with respect to silica. The oxide K_2O has a strong positive correlation, while Na_2O is more erratic. The sharp peak for sample FJV-14 is most likely an anomalous result due to excessive handling of the the XRF disc or other contamination.

When chemical elements are plotted with respect to elevation, several distinct patterns emerge, as well as a couple of surprises (Figures 4-7 through 4-12). Silica weight percentages are generally predictable, values corresponding well to field nomenclature. A sharp increase occurs at the "transition" (14 meters above the base) from two-feldspar granite (FJV-4) to kspar dominated granite (FJV-3), and then drops dramatically with the sudden appearance of gabbro (FJV-8) at 25.5 meters.

A decrease occurs between the two upper units, both with the same field designation of "heterogeneous diorite." The uppermost unit (FJV-27) has the least silica - 47.23 wt%, a value similar to that of the basaltic dike. Incompatible trace elements, such as Rb and Y, show a similar pattern, and Cr, a strongly compatible element, is most enriched in this sample (Figures 4-11 and 4-12). Most of the mafic oxides (FeO , MgO , CaO , and Al_2O_3) are concentrated in the upper section, as are MnO and P_2O_5 , while K_2O is

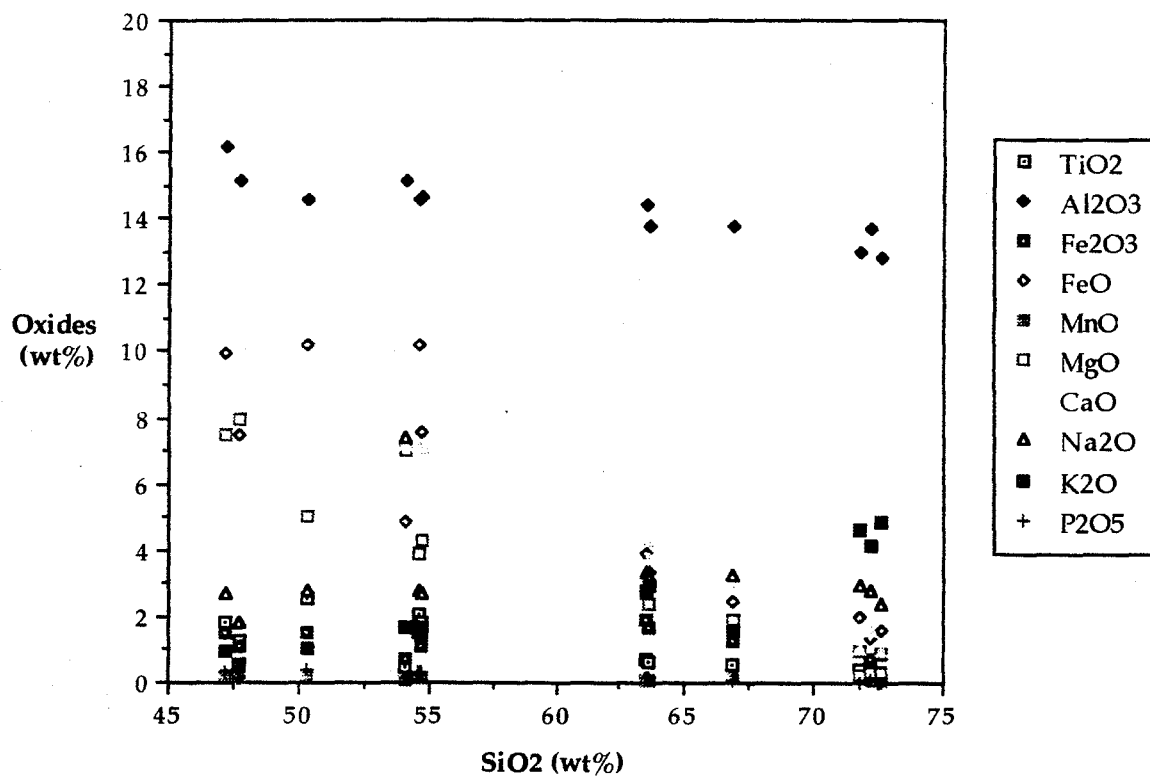


FIGURE 4-2: All units. Major Oxides vs. SiO2.

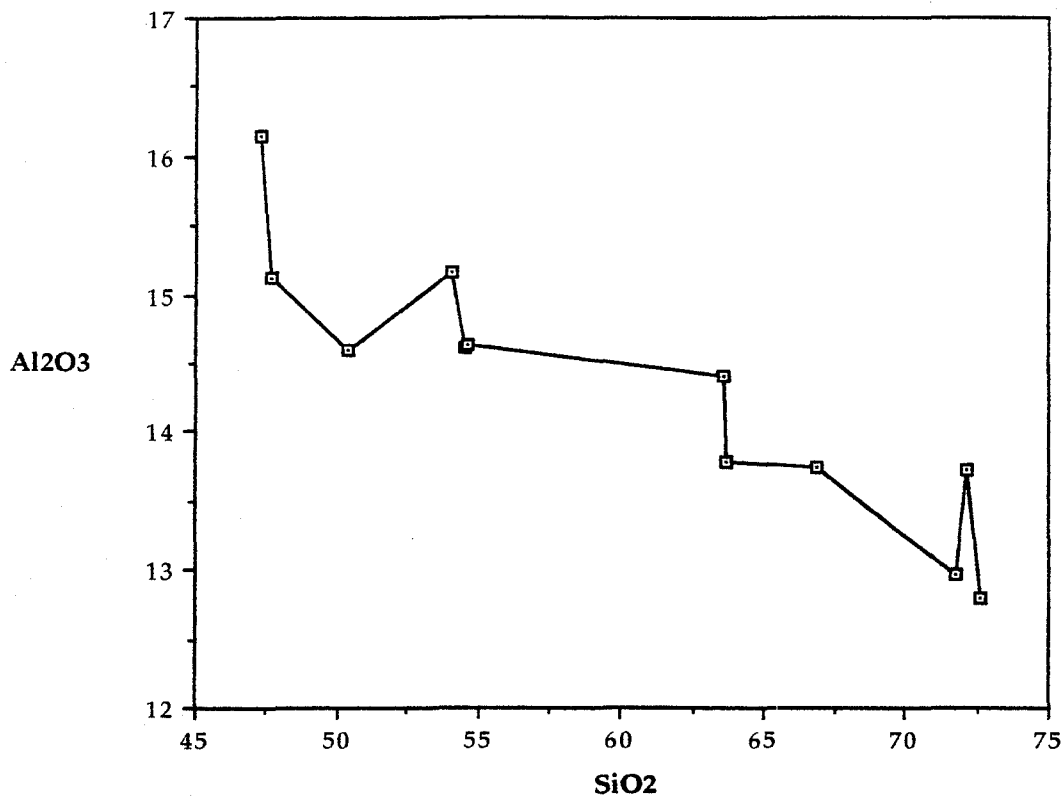


FIGURE 4-3: All units. Al₂O₃ vs. SiO₂, wt%.

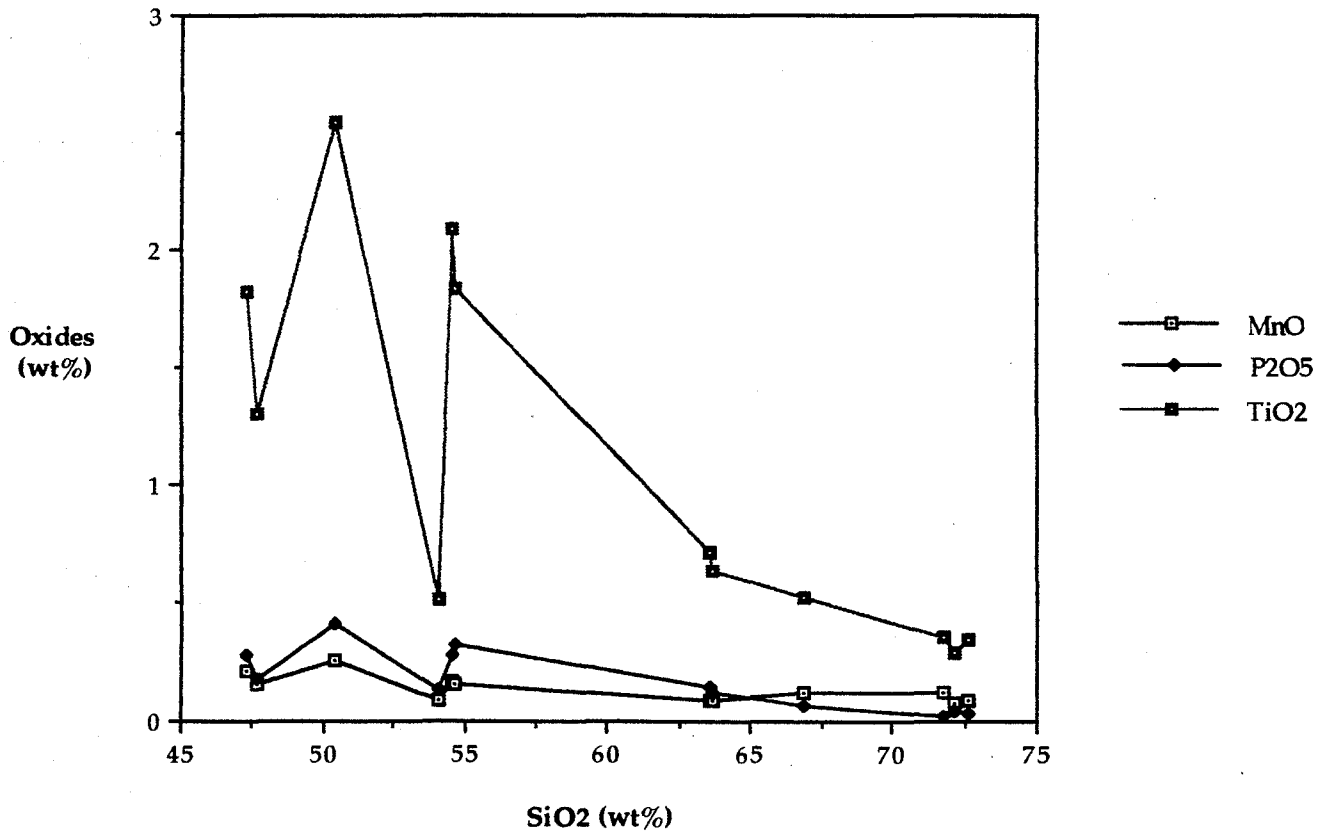


FIGURE 4-4: All units. Titanium, manganese, and phosphorous oxides vs. silica.

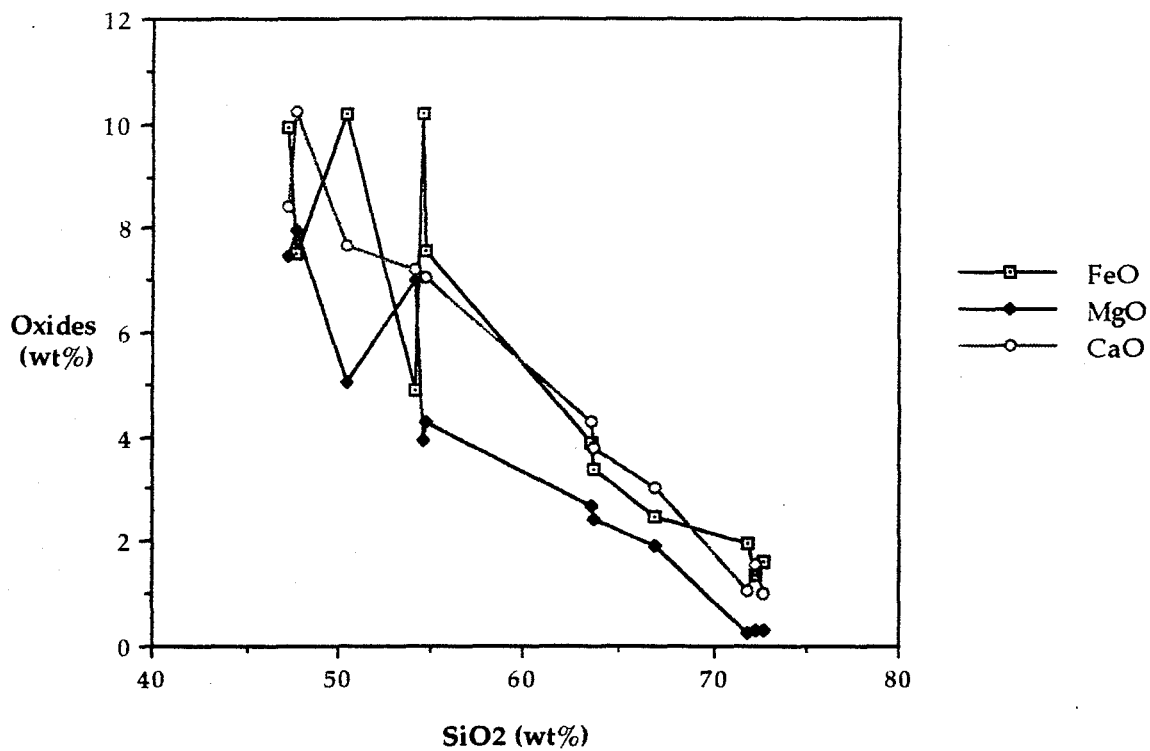


FIGURE 4-5: All Units. Mafic oxides vs. silica.

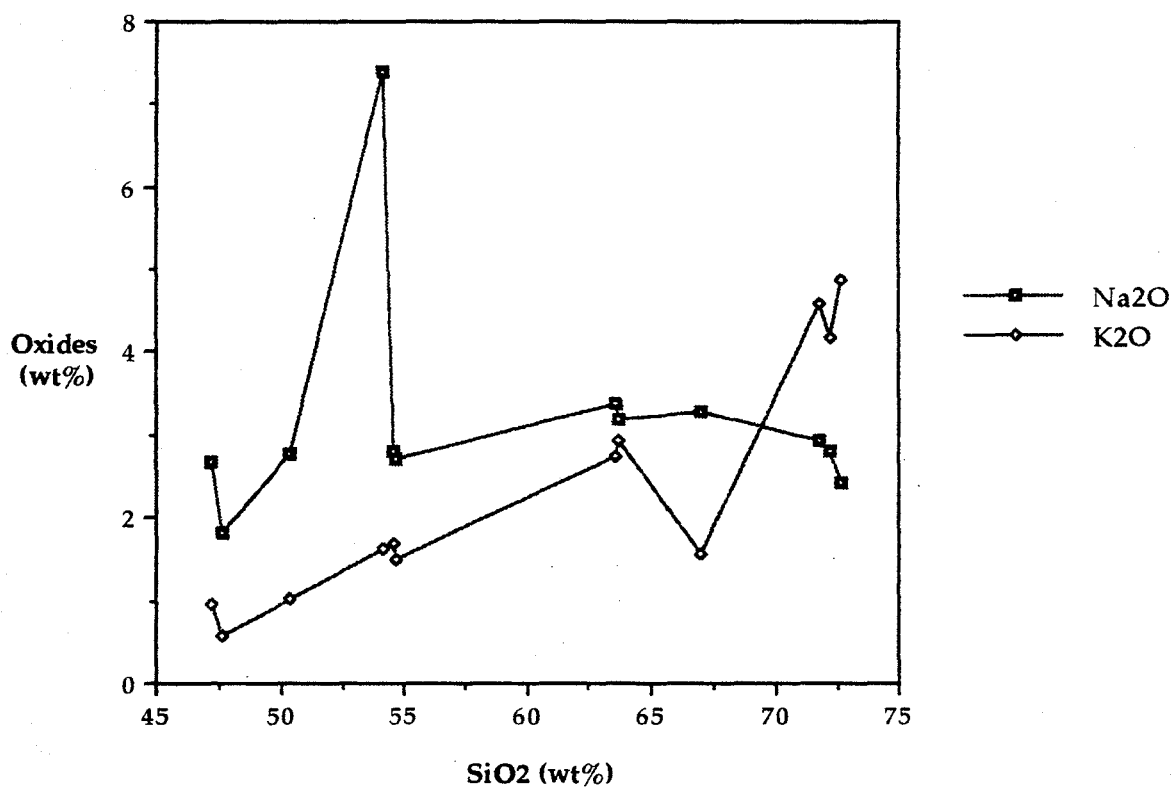


FIGURE 4-6: All Units. Sodium and potassium oxides vs. silica.

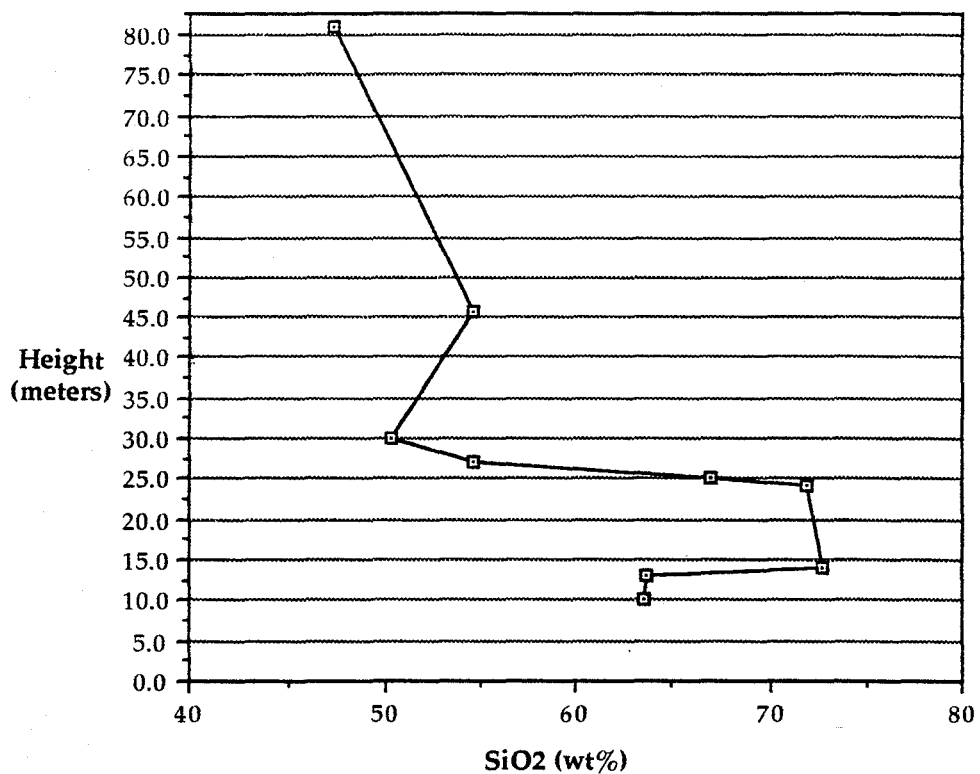


FIGURE 4-7: Silica plotted against height above the base of the section.

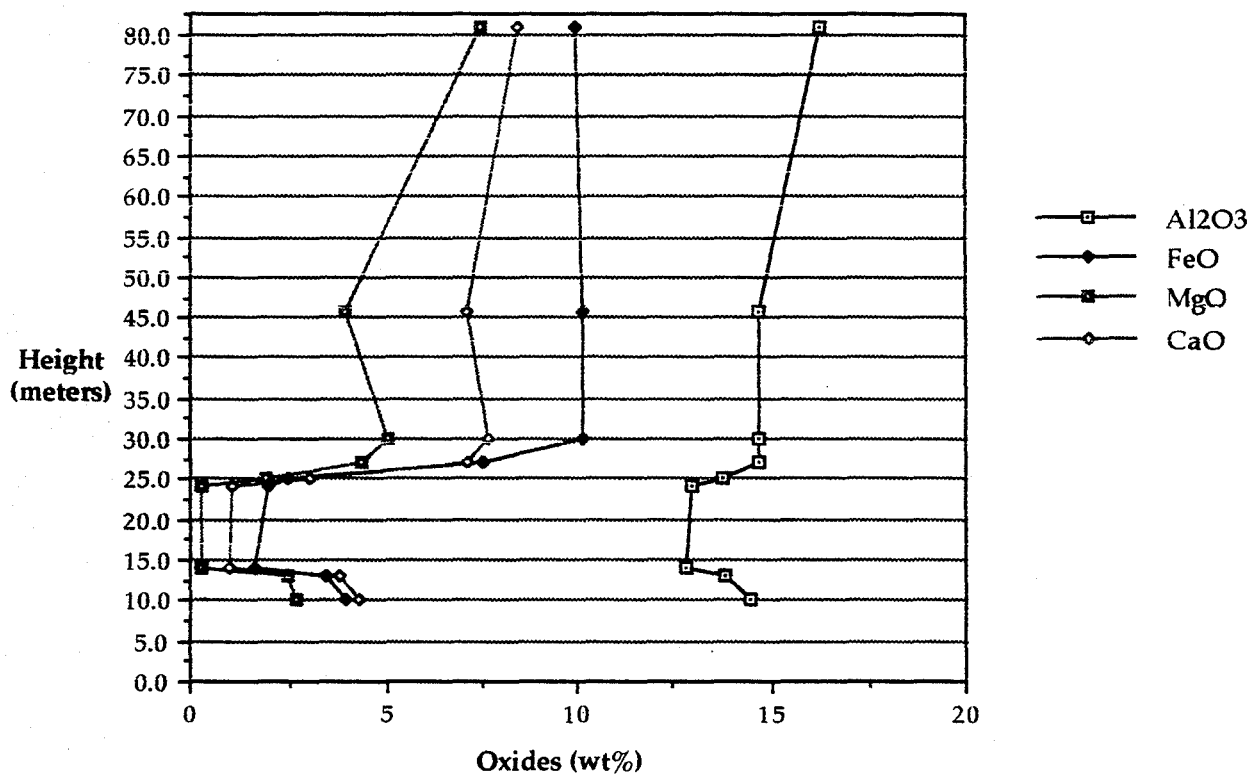


FIGURE 4-8: Oxides plotted against height above the base of the section.

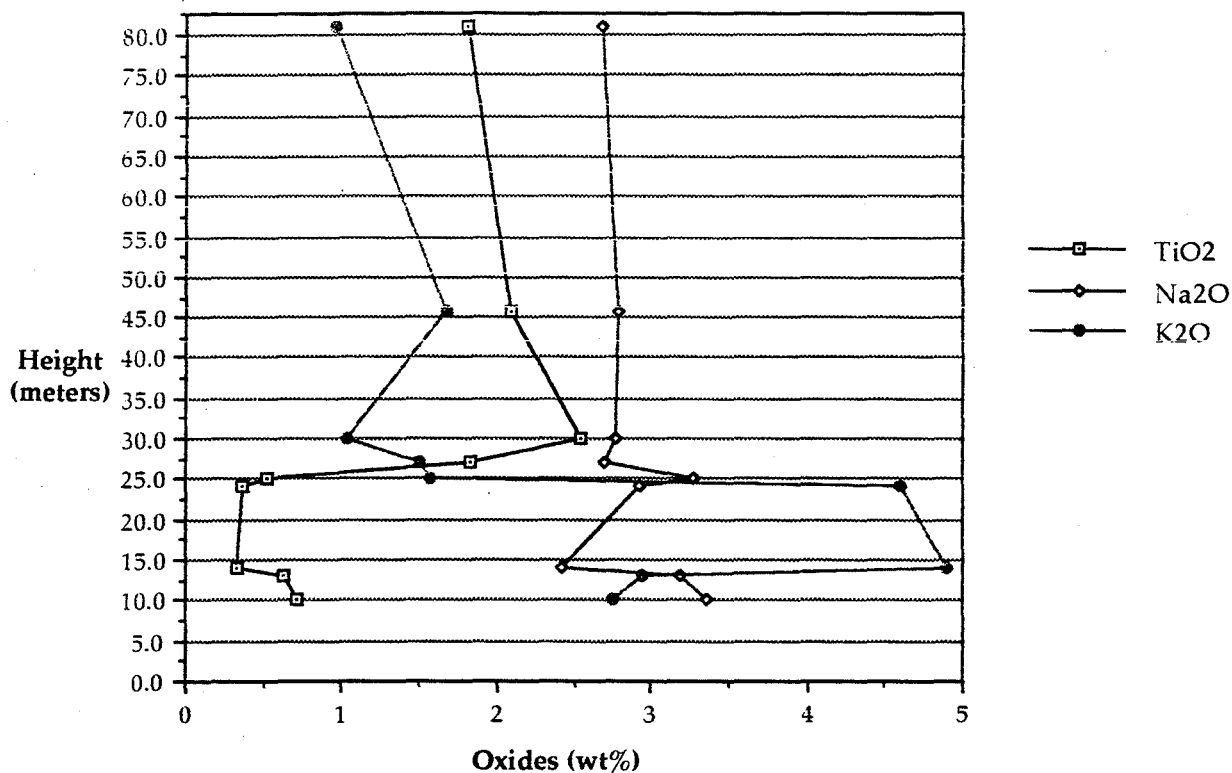


FIGURE 4-9: Oxides plotted against height above the base of the section.

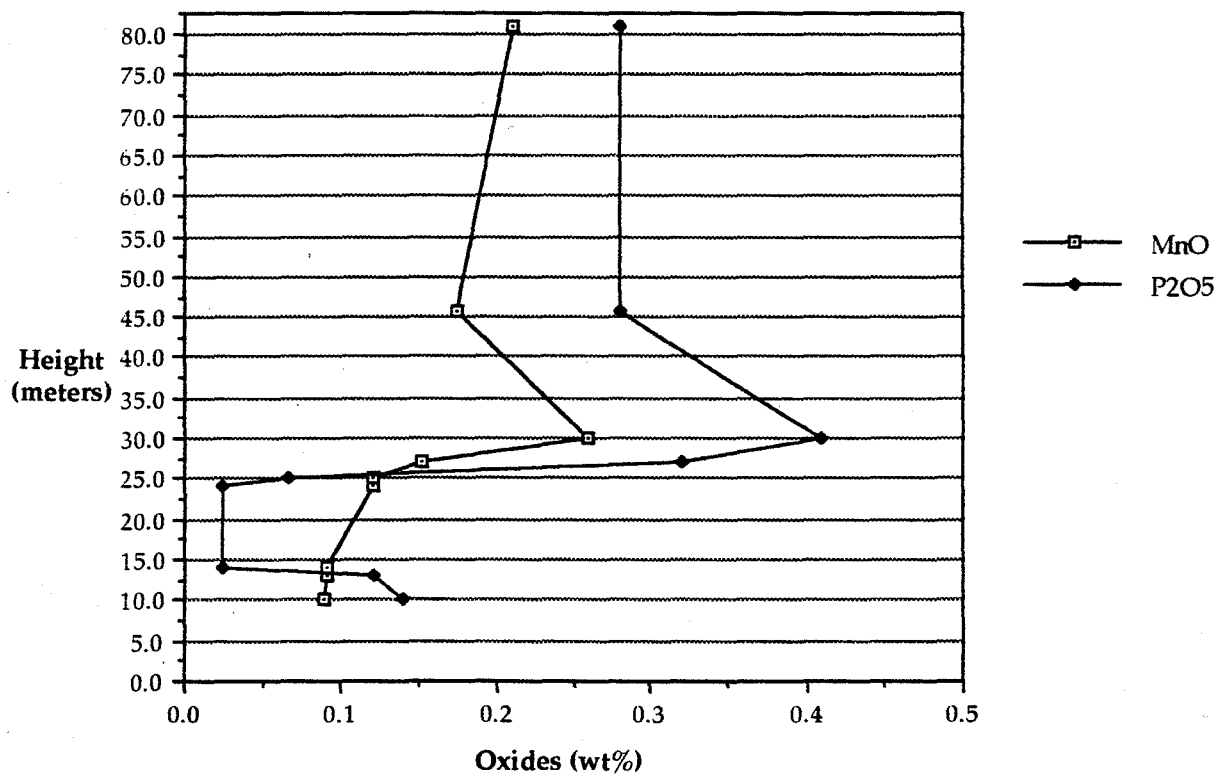


FIGURE 4-10: Oxides plotted against height above base of the section.

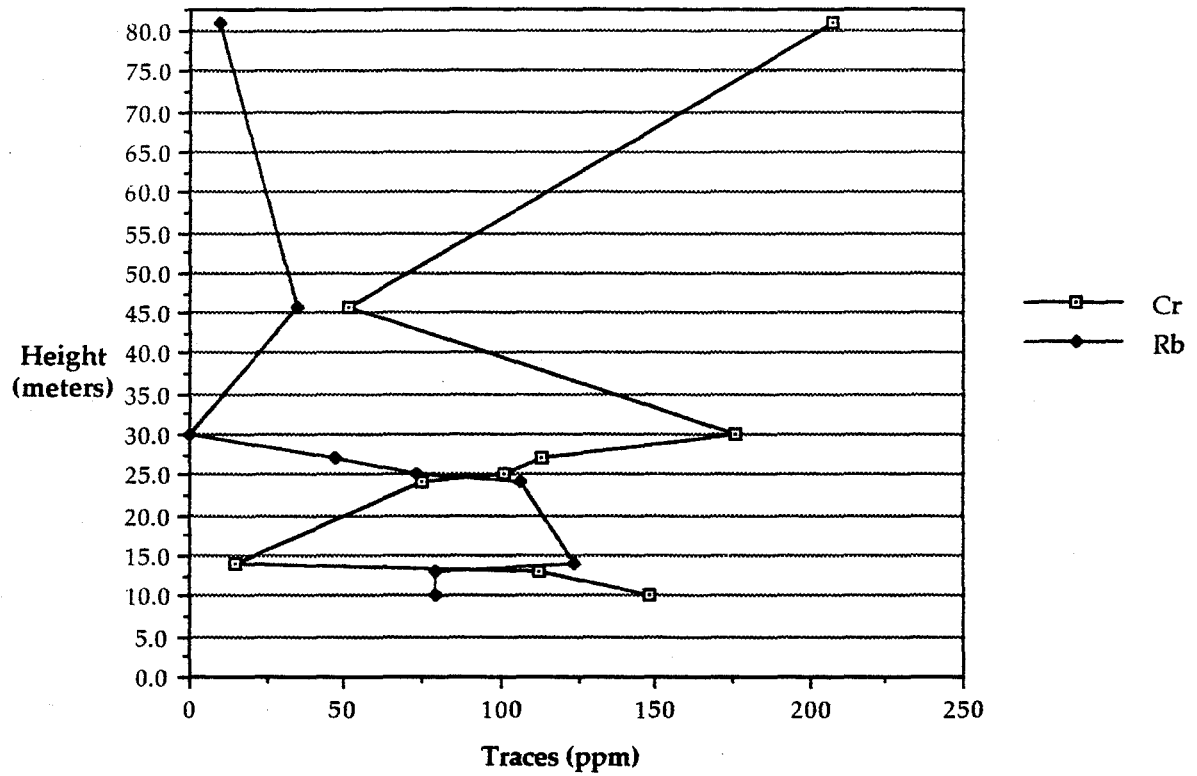


FIGURE 4-11: Trace elements plotted against height above the base of the section.

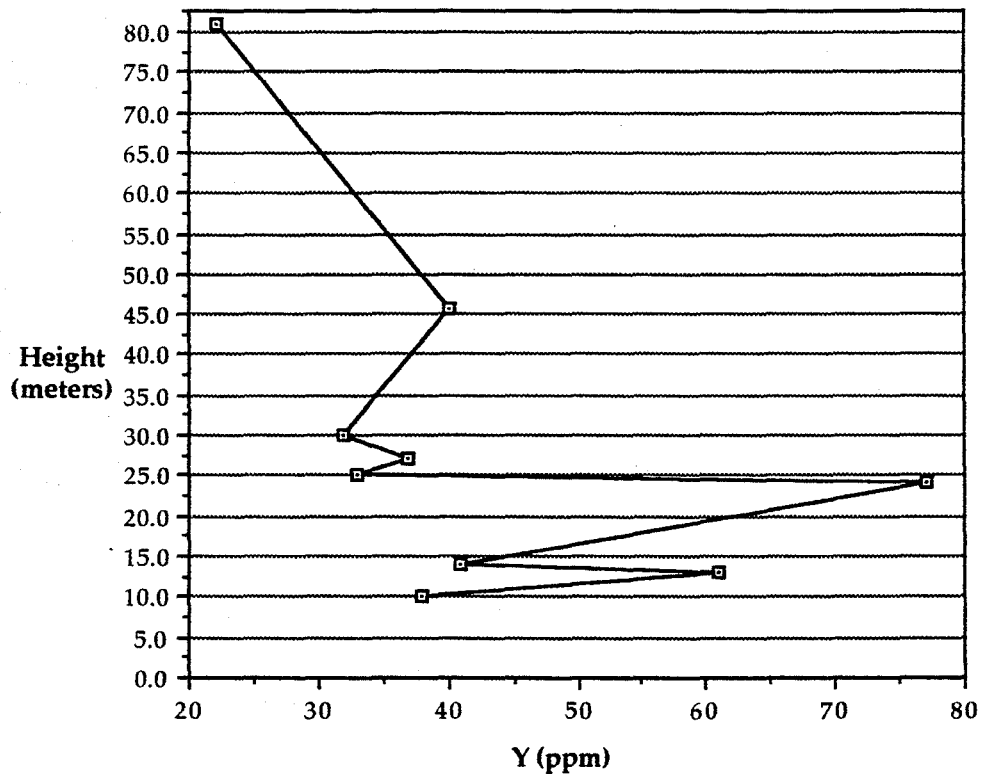


FIGURE 4-12: Yttrium plotted against height above the base of the section.

depleted here. All of these trends suggest an increase in mafic character in the uppermost portion of the section, a potential surprise as discussed in the next chapter.

Sodium oxide displays a perplexing trend; although one might expect it to mirror K_2O , it is in fact more similar to the mafic oxides, being depleted in the granitic units and concentrated in the gabbros.

On the Fe+Ti/Al/Mg triangular plot of Figure 4-13a, all units plot on the high iron tholeiitic trend. The A-F-M plot, Figure 4-13b, is more ambiguous; most units plot as calc-alkaline.

Basaltic and Gabbroic Units

FJV-1a, FJV-8, FJV-14, FJV-21

Silica values for these units range from 47.67 to 54.69 wt%. Al_2O_3 concentrations hover around 15 wt%, while K_2O and Na_2O range from less than 1 to 2 wt%. One notable exception is the composite dike's unreasonably high Na_2O value of 7.40 wt %. Magnesium oxides are higher in the dikes (7-8 wt%) than the coarse and chilled gabbros (4-5 wt%) suggesting at least a partial fractional crystallization relationship between the dikes and the gabbros. The two dikes are generally richer in compatible oxides than the gabbros.

Geochemical classifications for the four low silica samples are shown in Figure 4-14. The cross-cutting dike (FJV-1a) and the pillow chill (FJV-21) plot as basalts. The coarse gabbro (FJV-8) sits in the more intermediate, basaltic andesite field. Because of its anomalously high sodium oxide value, the mafic member of the composite dike (FJV-14) plots as a basaltic trachyandesite. Substituting a more reasonable Na_2O value for this sample would lower it into the basaltic andesite field.

CIPW norms are shown in Table 4-3. While FJV-1a, FJV-8, and FJV-21 are hypersthene/quartz normative, FJV-14 is olivine/nepheline normative.

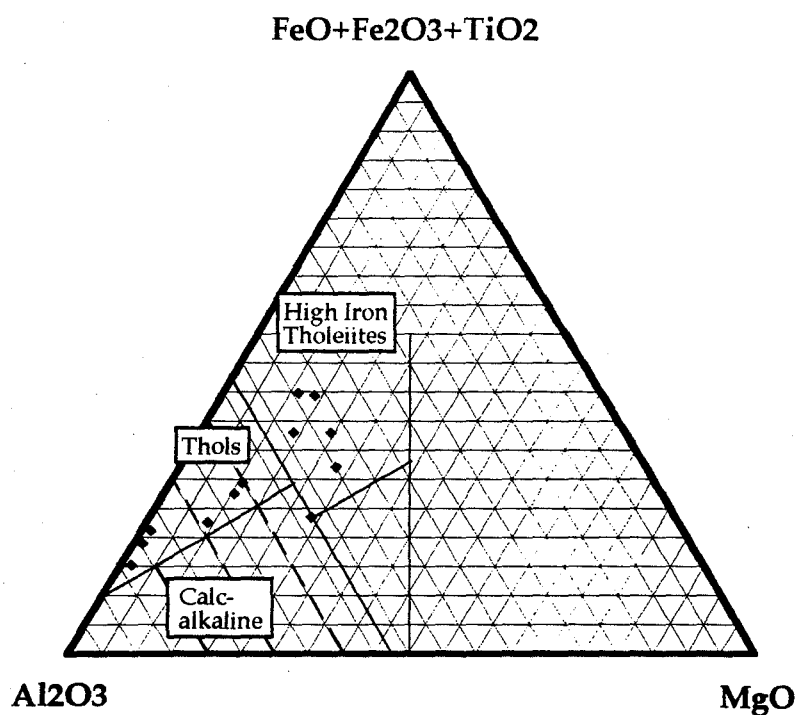


FIGURE 4-13a: All units plot as tholeiites. (Jensen, 1976).

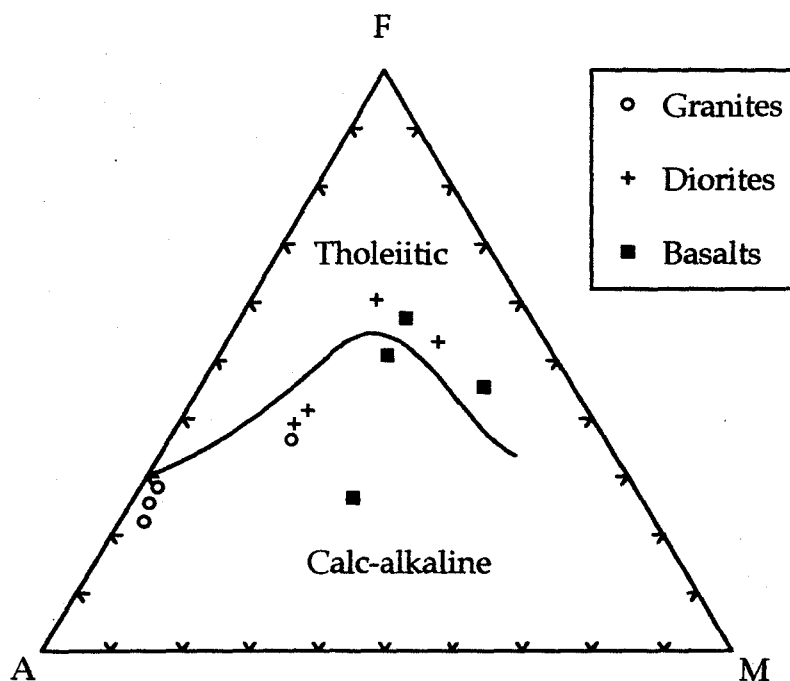


FIGURE 4-13b: AFM diagram showing tholeiitic and calc-alkaline fields. Classification for Sommes Cove units is ambiguous. (Irvine and Baragar, 1971)

TABLE 4-3

SOMMES COVE BASALTS - Major Element Compositions				
Sample #	FIV-1a	FIV-8	FIV-14	FIV-21
Description	Basalt Dike	Coarse Gabbro	Composite Basalt	Pillow Chill
SiO ₂	47.67	54.69	54.12	50.38
TiO ₂	1.30	1.83	0.51	2.54
Al ₂ O ₃	15.12	14.63	15.17	14.60
Fe ₂ O ₃	1.12	1.13	0.73	1.52
FeO	7.49	7.56	4.88	10.17
MnO	0.16	0.15	0.09	0.26
MgO	7.99	4.30	7.02	5.04
CaO	10.23	7.08	7.21	7.67
Na ₂ O	1.83	2.70	7.40	2.77
K ₂ O	0.58	1.50	1.64	1.03
P ₂ O ₅	0.18	0.32	0.13	0.41
LOI	1.85	1.62	1.10	1.88
Total	95.51	97.51	100.00	98.27
<u>CIPW Norms</u>				
Ap	0.4199	0.7461	0.3032	0.956
Il	2.48	3.48	0.9712	4.84
Mt	1.63	1.64	1.06	2.21
Or	3.43	8.86	9.69	6.08
Ab	15.49	22.84	32.39	23.44
An	31.34	23.37	3.33	24.36
Di	14.8	7.98	25.46	9.13
Hy	23.66	16.95	-	21.7
Ol	-	-	9.31	-
Ne	-	-	16.38	-
Q	0.4225	10.02	-	3.67
TOTAL	93.67	95.89	98.9	96.39
A	12.59	24.26	41.56	18.36
M	41.76	24.83	32.27	24.35
F	45.65	50.91	26.17	57.29
Q	49.26	51.8	46.62	49.22
M	24.23	18.06	20.59	23.01
L	26.52	30.14	32.79	27.78

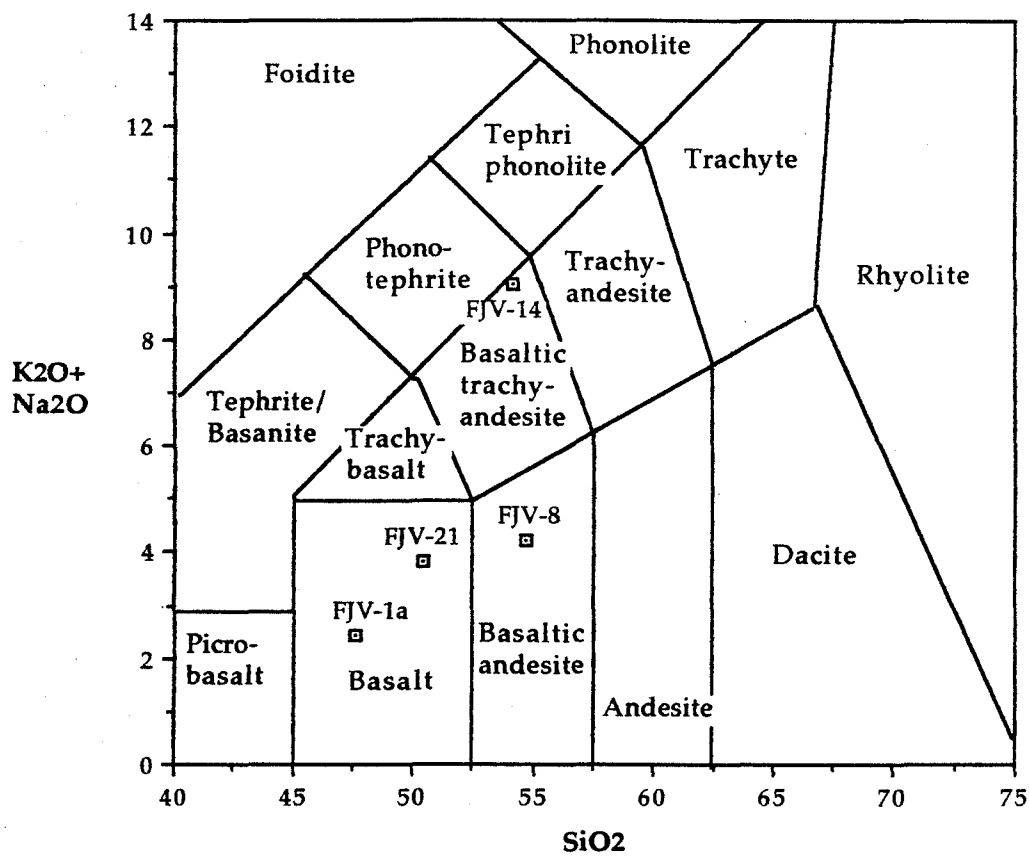


FIGURE 4-14: Basalt classification diagram. FJV-14, with a reasonable Na_2O value, would plot as a Basaltic Andesite. (McBirney, 1984)

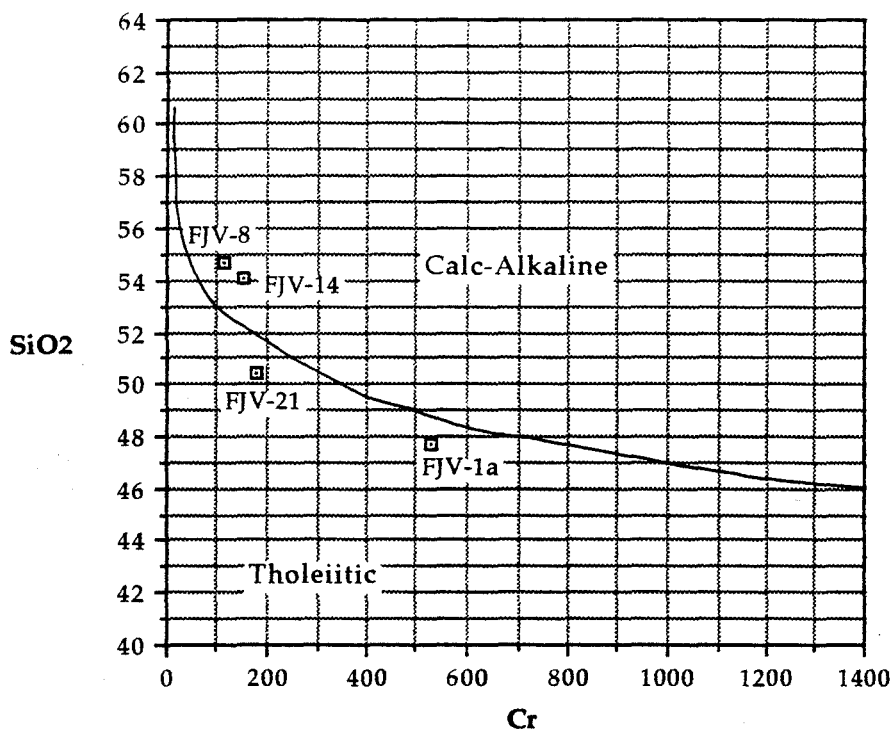


FIGURE 4-15: Silica vs. chromium. Sommes Cove basalts plot in both tholeiitic and calc-alkalic fields.

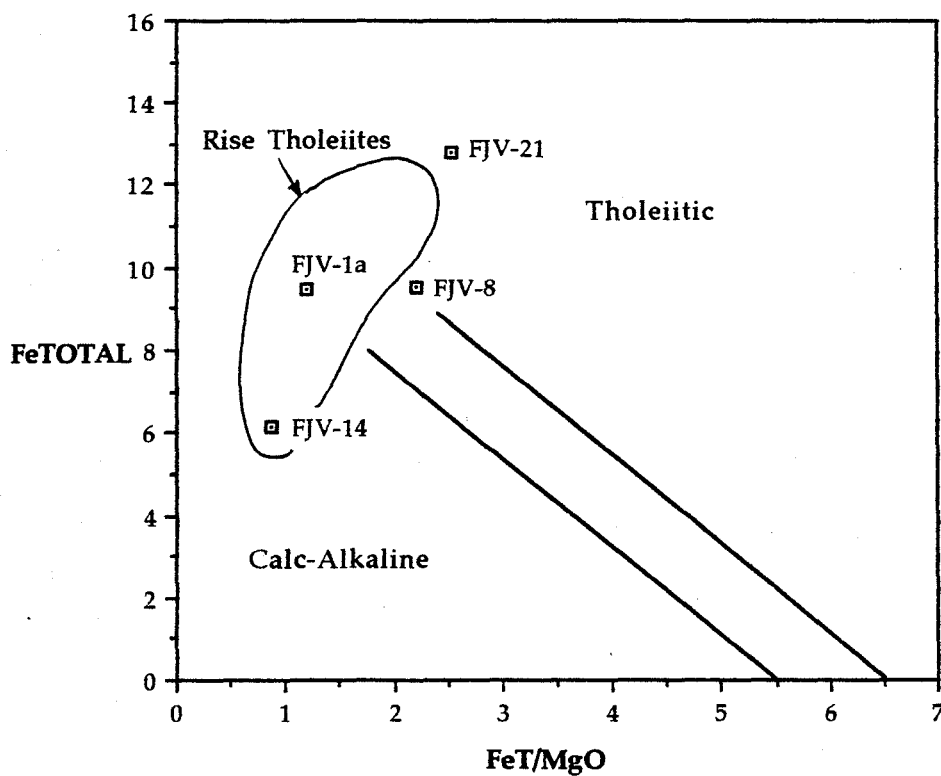


FIGURE 4-16: Total iron oxide vs. total iron over magnesium oxide. Sommes Cove basalts in or near the Rise Tholiite field.

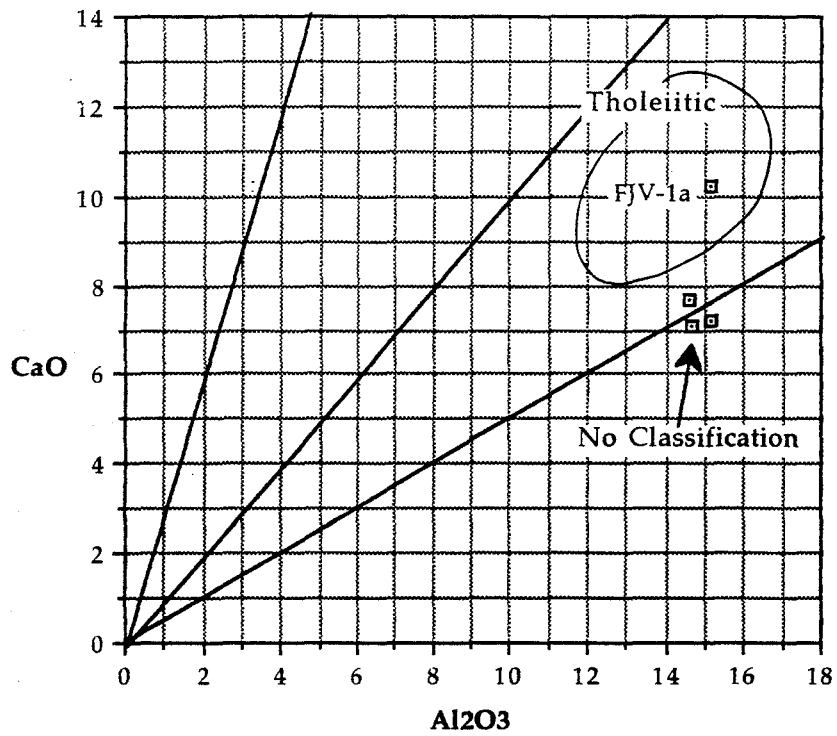


FIGURE 4-17: Calcium oxide vs. aluminum oxide. Only the basaltic dike fits into a discrete field: Tholeiite.

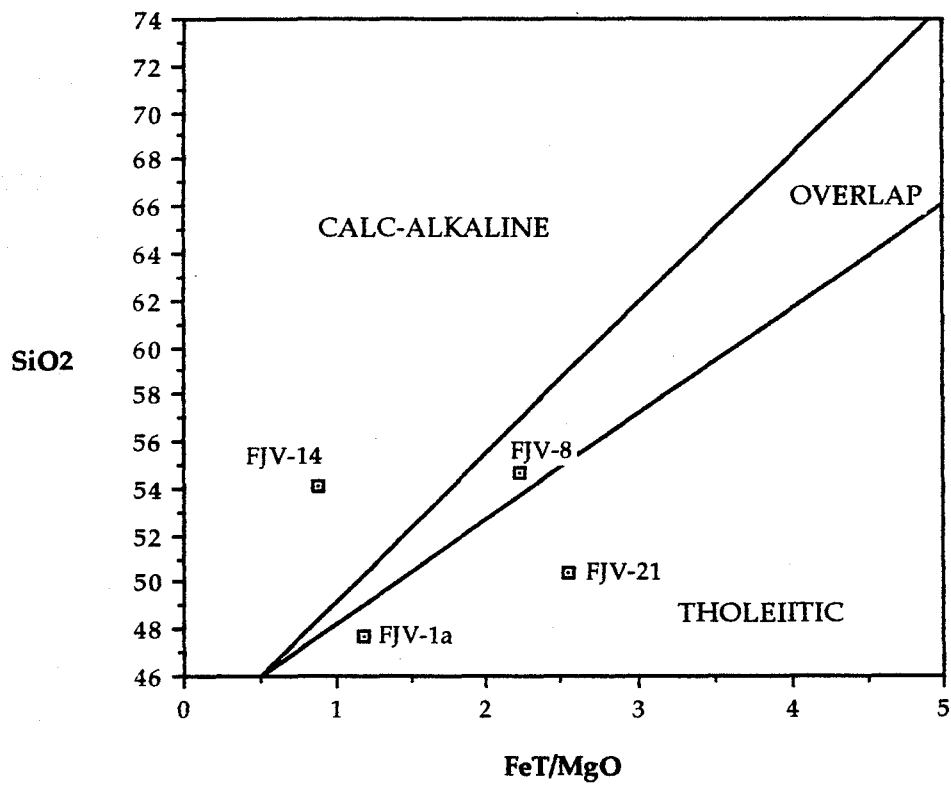


FIGURE 4-18: Silica vs. total iron over magnesium oxide. The basaltic dike plots as a tholeiite, the composite as calc-alkaline.

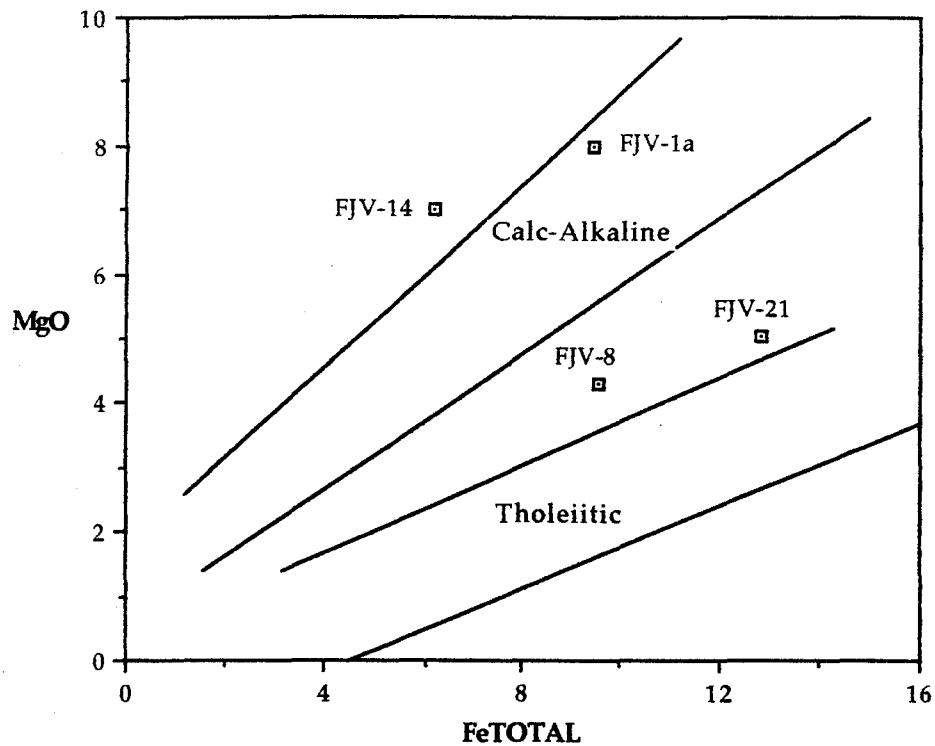


FIGURE 4-19: MgO vs. total iron. The basaltic dike plots as calc-alkaline.

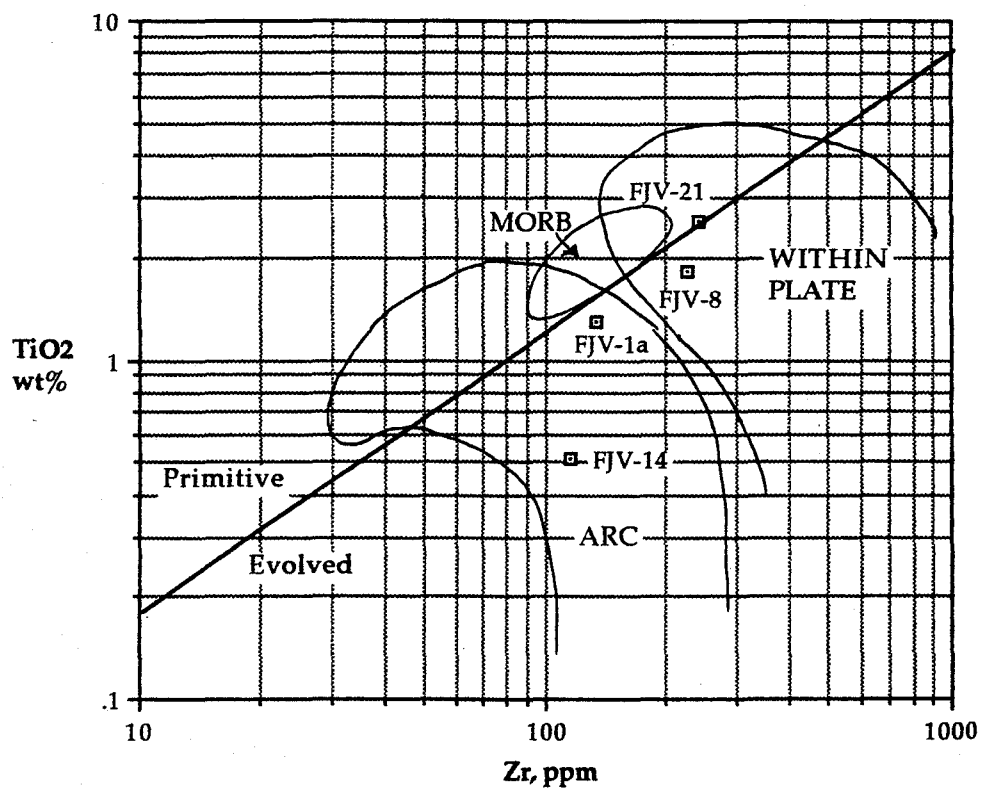


FIGURE 4-20: TiO2 vs. zirconium.

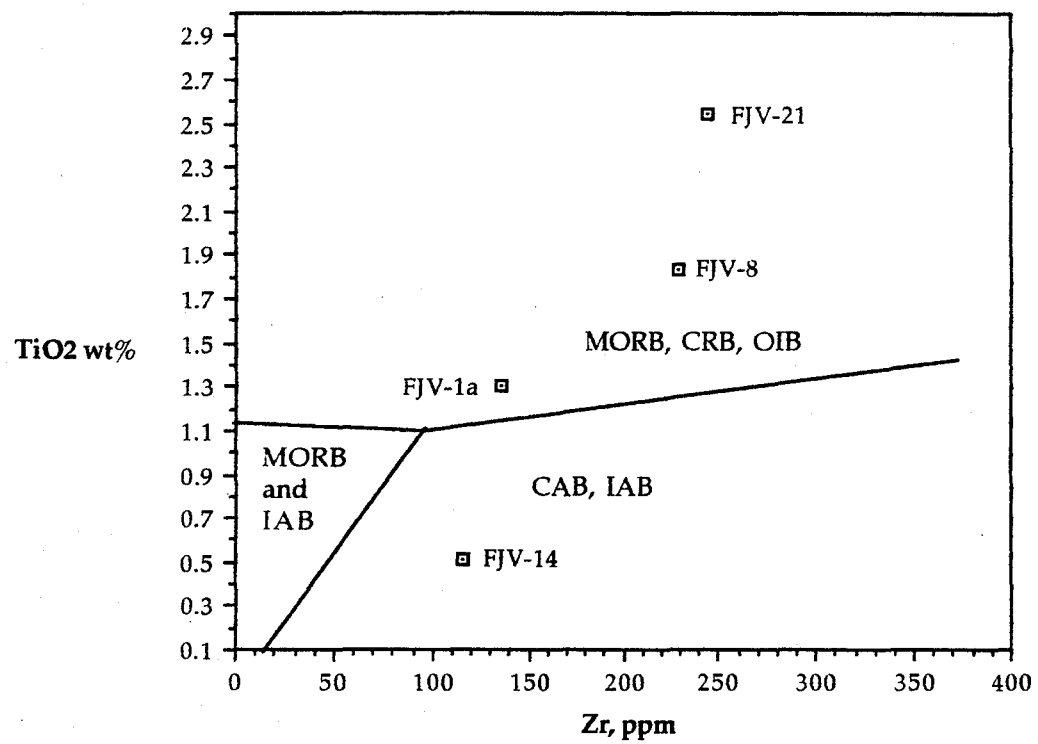


FIGURE 4-21: TiO₂ vs. zirconium.

This is most likely a consequence of the aberrant sodium oxide value, as nepheline is a sodium feldspathoid.

Attempts to classify mafic units with respect to tectonic setting using published discrimination diagrams yield inconclusive results (Figures 4-15 through 4-21). Although the basaltic dike, FJV-1a, frequently plots as a tholeiite, it also plots in calc-alkaline fields, and in both arc and rift fields. The mafic member of the composite dike, however, consistently plots in calc-alkaline and continental arc fields. The other two units exhibit random scatter, revealing no noticable affinities.

Intermediate Units

FJV-4, FJV-5, FJV-23, FJV-27

Silica values for the "diorites" of Sommes Cove range from 47.23 to 63.64 wt%. The low SiO₂ value and high mafic oxide concentrations for FJV-27 indicate that, although dubbed "diorite" in the field, it is in many respects the most mafic unit analyzed geochemically. It has the lowest SiO₂ concentration, is highest in Al₂O₃, has very high MgO and CaO concentrations, and is very low in Na₂O and K₂O.

Table 4-4 shows the major oxides and CIPW norms for these units. While the other samples from this groups are hypersthene/quartz normative, FJV-27 has a hypersthene/olivine norm. It is, however, orthoclase normative, consistent with the large (up to 4 mm) kspars crystals seen petrographically and in hand sample. Unlike the macroscopically similar FJV-23, no quartz is found in FJV-27's thin section.

TABLE 4-4

SOMMES COVE "DIORITES"-Major Element Compositions				
SAMPLE#	FJV-4	FJV-5	FJV-23	FJV-27
Description	2felds Granite	TransGranite	HeteroMatrix	MostMaficMatrix
SiO2	63.64	63.54	54.57	47.23
TiO2	0.63	0.71	2.09	1.82
Al2O3	13.78	14.41	14.61	16.15
Fe2O3	1.69	1.94	1.52	1.49
FeO	3.38	3.89	10.16	9.94
MnO	0.09	0.09	0.17	0.21
MgO	2.41	2.68	3.93	7.46
CaO	3.76	4.27	7.08	8.42
Na2O	3.19	3.37	2.80	2.69
K2O	2.94	2.75	1.68	0.96
P2O5	0.12	0.14	0.28	0.28
LOI	1.26	1.22	0.67	3.33
TOTAL	96.89	99.01	99.56	99.98
<u>CIPW Norms</u>				
Ap	0.2798	0.3264	0.6528	0.6527
Il	1.20	1.35	3.98	3.46
Or	17.37	16.24	9.92	5.67
Ab	26.99	28.51	23.69	22.75
An	14.60	16.07	22.33	29.15
Di	2.74	3.53	9.29	8.94
Hy	13.73	15.38	25.44	6.19
Ol	-	-	-	20.93
Q	19.09	16.81	4.71	-
TOTAL	96.00	98.22	100.01	97.74
A	43.85	40.64	21.12	15.45
M	17.24	17.80	18.53	31.57
F	38.91	41.57	60.35	52.98
Q	55.20	54.49	50.27	50.41
M	9.34	10.69	21.43	23.51
L	35.46	34.82	28.31	26.08

Granitic Units

FJV-3, FJV-6, FJV-7, FJV-15

All granitic units analyzed plot peraluminous and subalkaline (Figures 4-22 and 4-23). Silica concentrations for this group range from 66.89 to 72.64 wt%. FJV-7, the unit sandwiched between the granitic unit and the large, gabbroic layer (Figure 2-2) has the highest concentrations in the mafic oxides TiO_2 , total Fe, MgO, and CaO and is lowest in SiO_2 and K_2O . The other three samples display very similar major oxide chemistries.

Tectonic discrimination diagrams yield some conclusive data for the "unmixed" units. The felsic member of the composite dike, FJV-15, and FJV-6, the only unit with the field name "granite," plot consistently in or near rift setting fields (Figures 4-24 through 4-28). The other two units exhibit no discernible consistency. Figures 4-29 and 4-30 show that most of the granite samples plot as within plate granites (consistent with the CMG's A-type classification), while FJV-7 plots on the within plate granites and volcanic arc granites boundary.

Table 4-5 shows the CIPW norms for these units. Norms plot near the one kilobar minima of the Q-Ab-Or in Figure 4-31; this supports published data that asserts the CMIC was shallowly emplaced (WIEBE, 1993). Each sample is corundum normative, consistent with their peraluminous chemistries.

CHEMICALMODELLING

Mathematical modelling of unit trace element chemistries believed to be the result of mixing was accomplished using a Microsoft Excel spreadsheet prepared by Diane R. Smith of Trinity University in San Antonio, Texas. This spreadsheet models the effects of fractional crystallization, assimilation of

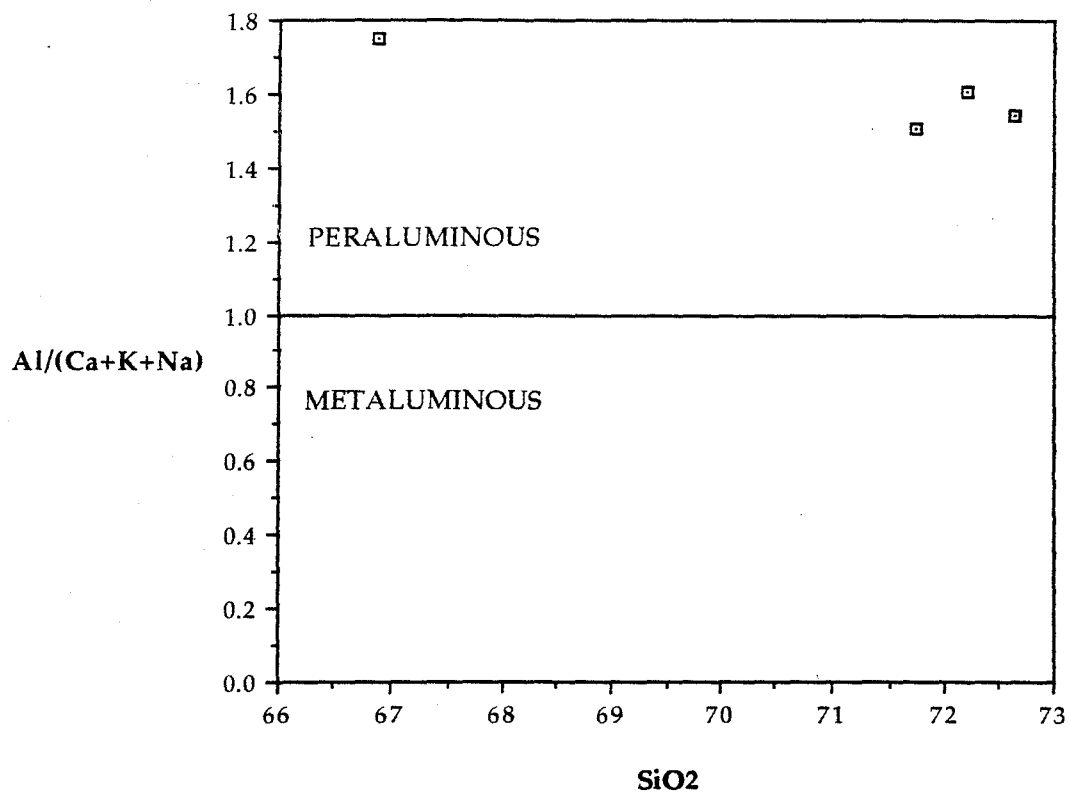


FIGURE 4-22: All granitic units plot as peraluminous.
(Irvine and Baragar, 1971)

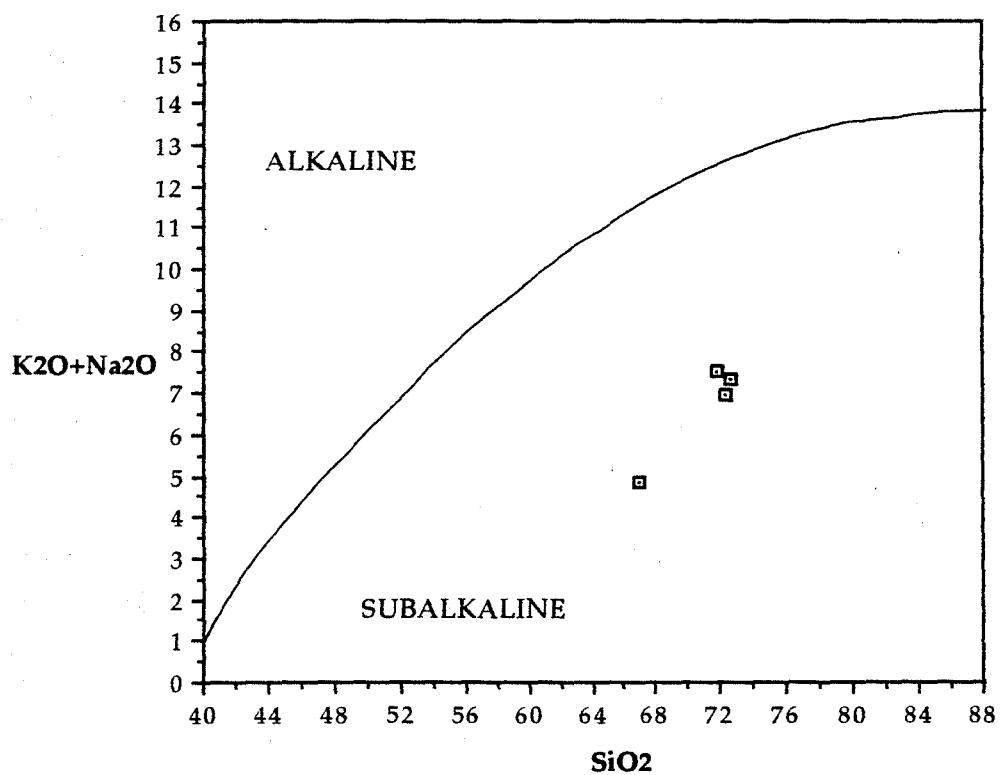


FIGURE 4-23: All granitic units plot as subalkaline.
(Irvine and Baragar, 1971)

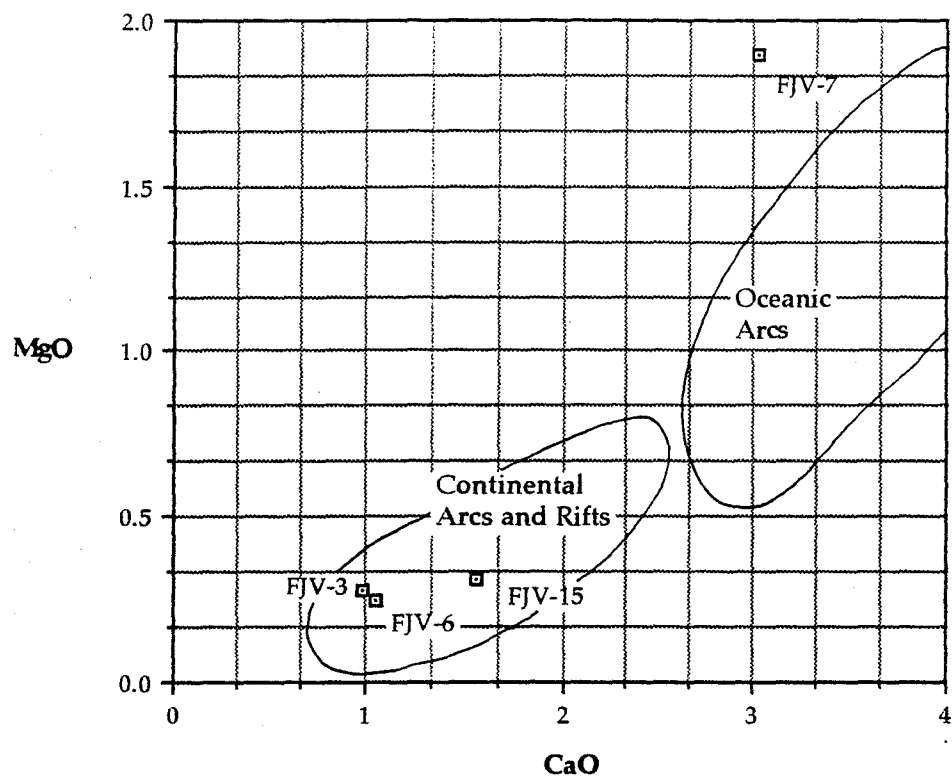


FIGURE 4-24: Magnesium oxide vs. calcium oxide. Most units plot in the arc/rift field.

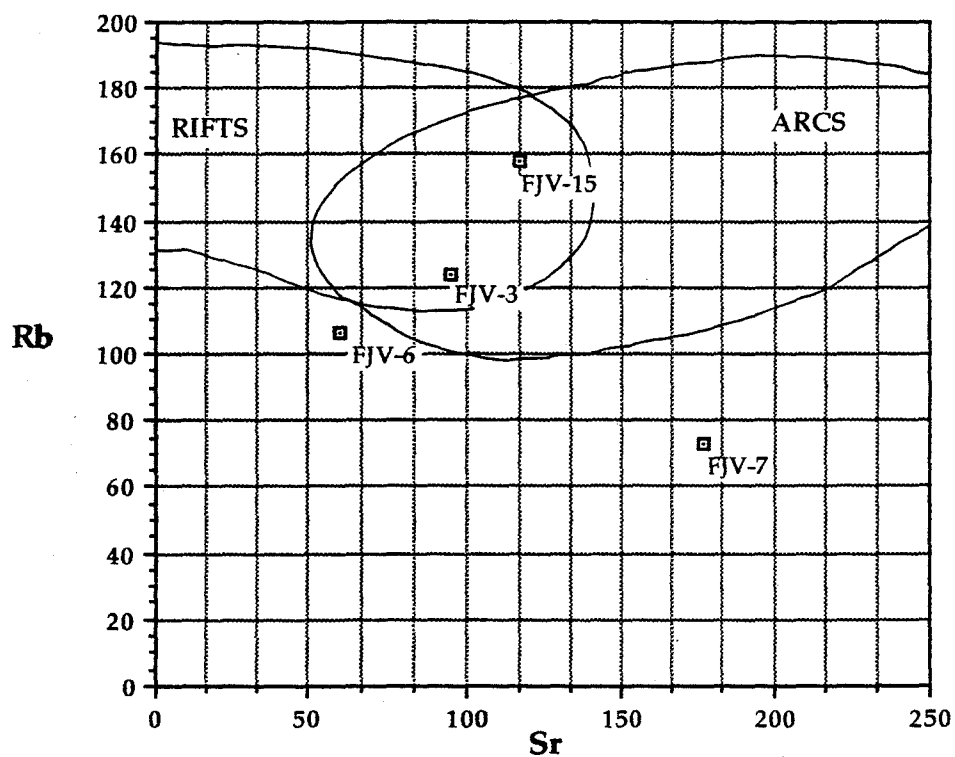


FIGURE 4-25: Rubidium vs. strontium. Again, most units plot in or near arc/rift fields.

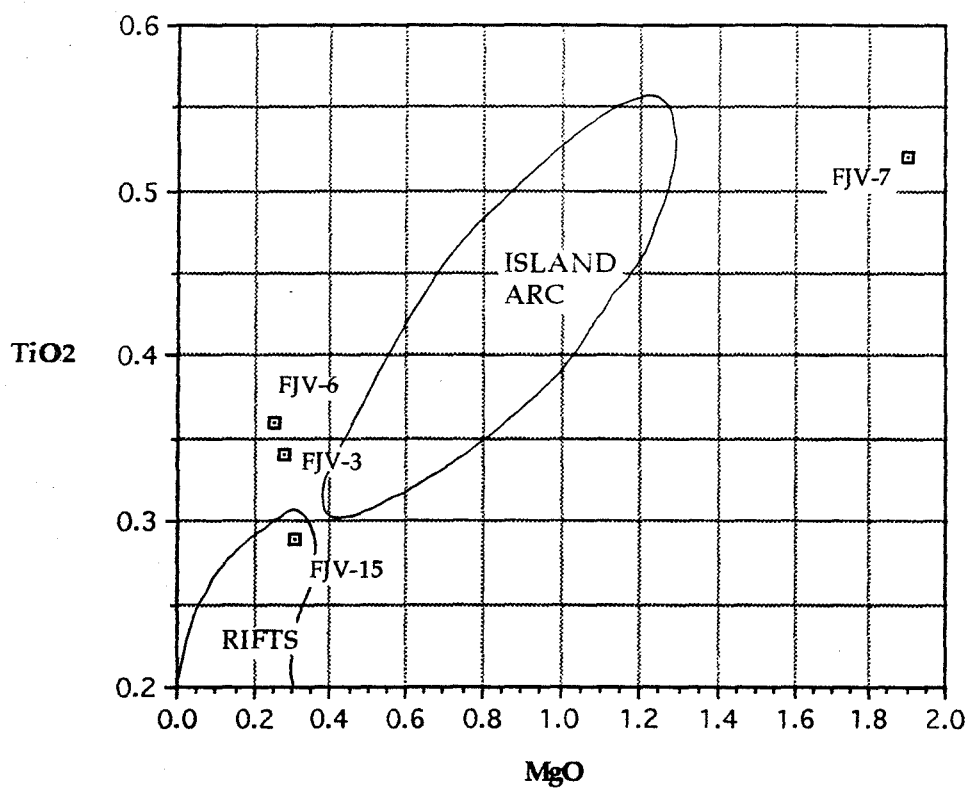


FIGURE 4-26: Titanium oxide vs. magnesium oxide. Most units plot near the rift or arc field.

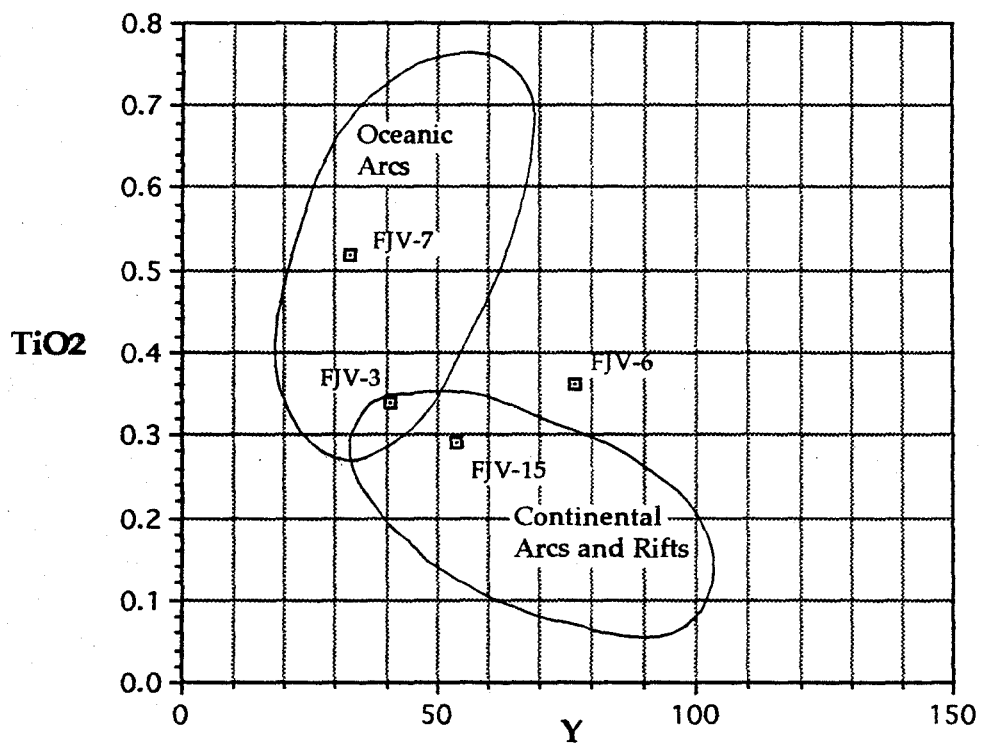


FIGURE 4-27: Titanium oxide (wt%) vs. yttrium (ppm).

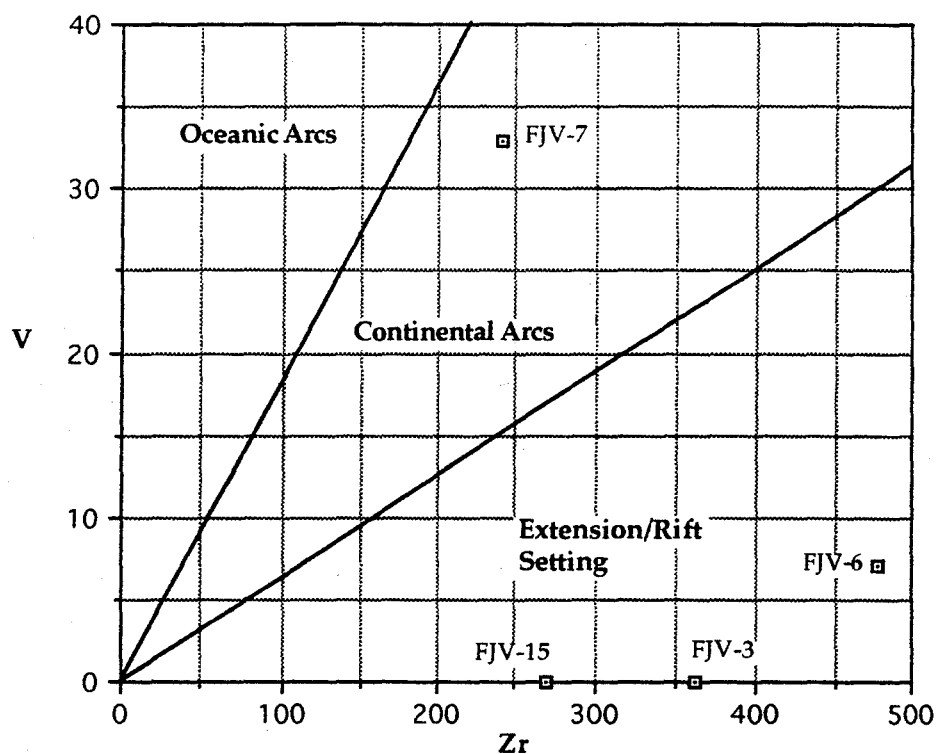


FIGURE 4-28: Vanadium vs. Zirconium (ppm)

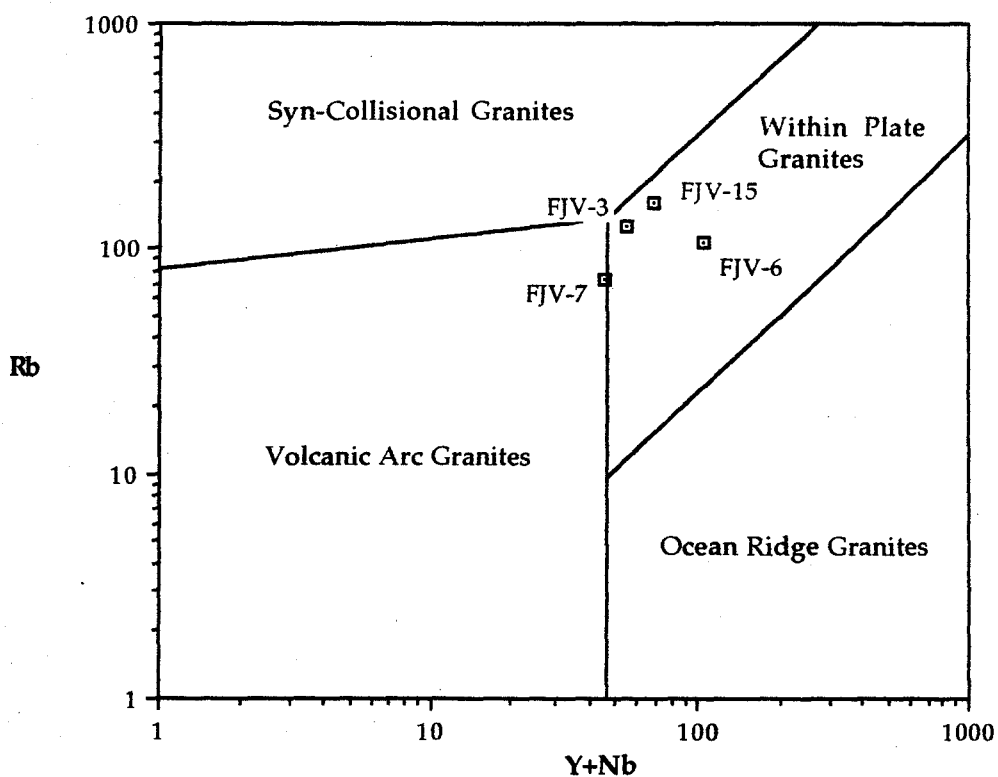


FIGURE 4-29: All units plot in or near the within plate field.

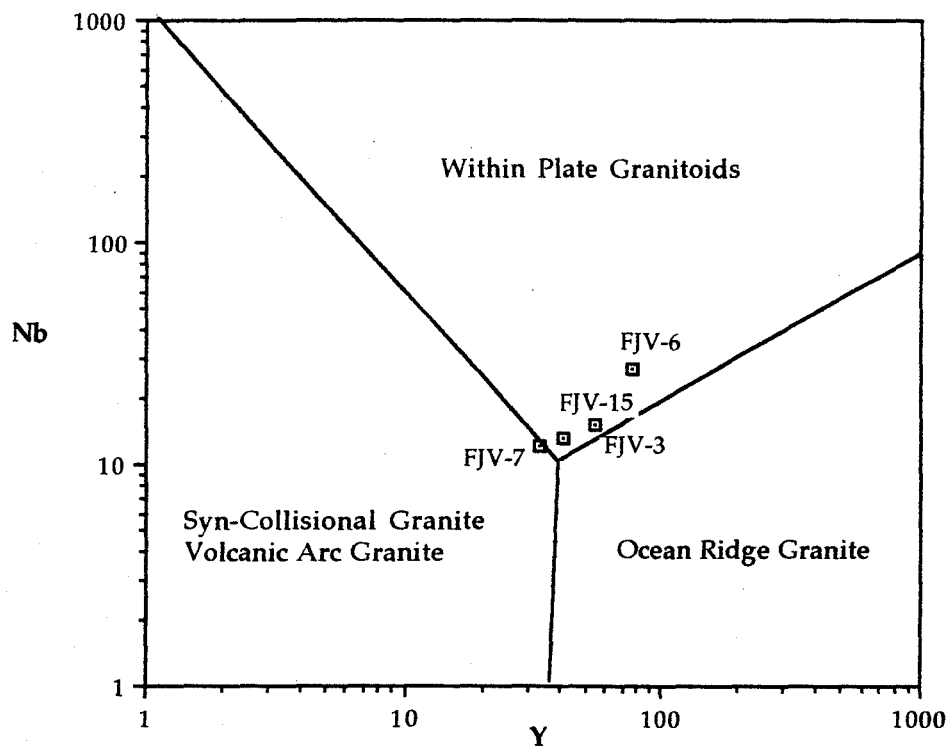


FIGURE 4-30: Niobium vs. yttrium (ppm).
(Pearce et al., 1984)

TABLE 4-5

SOMMES COVE GRANITES - Major Element Compositions				
Sample #	FIV-3	FIV-6	FIV-7	FIV-15
Description	Transition Granite	Granite	Intermediate	Composite Dike Aplite
SiO ₂	72.64	71.74	66.89	72.20
TiO ₂	0.34	0.36	0.52	0.29
Al ₂ O ₃	12.80	12.96	13.75	13.73
Fe ₂ O ₃	0.85	0.98	1.24	0.68
FeO	1.63	1.96	2.47	1.36
MnO	0.09	0.12	0.12	0.08
MgO	0.28	0.25	1.90	0.31
CaO	0.99	1.06	3.03	1.56
Na ₂ O	2.43	2.93	3.28	2.80
K ₂ O	4.89	4.60	1.56	4.18
P ₂ O ₅	0.03	0.02	0.07	0.04
LOI	0.46	0.52	0.95	0.55
Total	97.42	97.50	95.77	97.78
<u>CIPW Norms</u>				
Ap	0.0699	0.0466	0.1632	0.0933
Il	0.65	0.69	0.99	0.55
Mt	1.24	1.42	1.80	0.99
Or	28.89	27.17	9.21	24.69
Ab	20.56	24.79	27.75	23.69
An	4.72	5.13	14.57	7.48
Hy	2.59	3.04	7.60	2.38
C	1.75	1.26	1.30	1.83
Q	36.51	33.44	31.44	35.53
TOTAL	96.97	96.98	94.83	97.23
A	71.94	69.54	45.71	74.21
M	2.75	2.31	17.94	3.30
F	25.34	28.16	36.34	22.49
Q	58.34	57.70	57.82	58.07
M	2.88	3.32	6.38	2.45
L	38.78	38.98	35.79	39.48

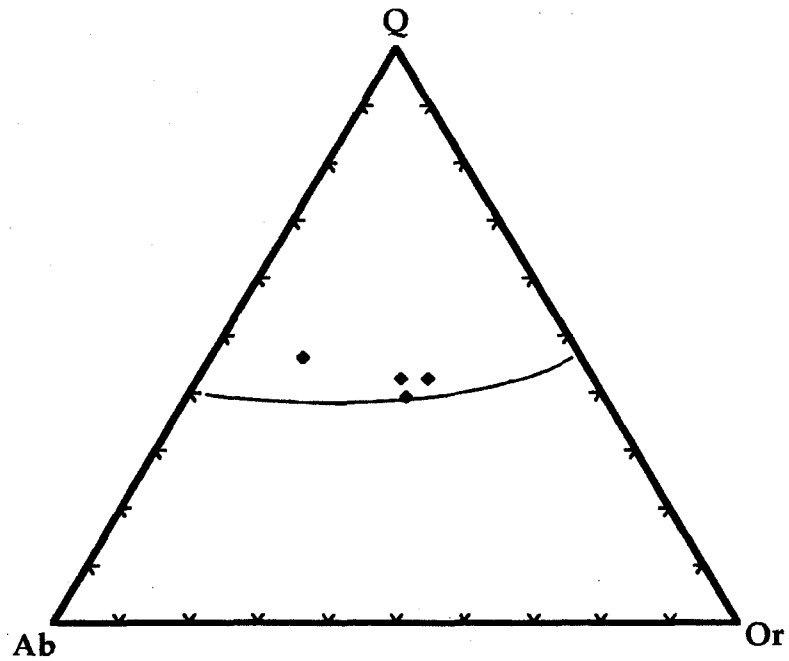


FIGURE 4-31: Quartz - Albite - Orthoclase normative plot. Sommes Cove felsic units plot near the 1kb minima. (McBirney, 1984)

country rock, and intrusion of a second magma on the trace element concentrations of a given chemistry. It considers many adjustable variables: initial, secondary, and assimilated rock chemistries; trace element and their affinities for crystalline phases in mafic and felsic melts (distribution coefficients); crystallizing phases and their ratios; and ratios of rate of fractional crystallization to rate of assimilation, rate of eruption, and rate of mixing with the secondary magma.

The aim of this exercise was to create the trace element signatures of theoretically mixed units using mafic and felsic end-members, with the mafic member in progressive states of fractionation. The basaltic dike chemistry (FJV-1a) was selected for the mafic end-member because its chemistry is similar to the gabbroic units, suggesting a genetic relationship, and previous authors suggest these dikes may have fed the gabbroic units observed (WIEBE and CHAPMAN, 1993). The Sommes Cove granitic unit, FJV-6, was used for the felsic end-member; it is in close proximity to the mixed units, and fractional crystallization modelling suggests it is a reasonable fractionate of the Cadillac Mountain Granite (Table 4-6), thought to be the host liquid when the gabbroic units intruded.

Seven of the ten trace elements provided by XRF analysis were used in modelling: V, Co, Zr, Rb, Sr, Y, and Nb. These were the only traces for which distribution coefficients were found.

Chilled Gabbro

Chilled gabbro chemistry is represented by sample FJV-21. Petrography of this unit reveals several felsic glomerophyrocysts of quartz, kspars, and biotite and large plagioclase phenocrysts in a plagioclase/amphibole/pyroxene groundmass. The gloms suggest some mixing, and the plagioclase phenocrysts suggest fractional crystallization.

Pure FC	CMG	95%	FJV-6	Error
<i>V</i>	8	7.1	7	1.43%
<i>Co</i>	0	0	0	0.00%
<i>Zr</i>	471	483.5	478	1.15%
<i>Rb</i>	95	95	99	4.04%
<i>Sr</i>	58	49	60	18.93%
<i>Y</i>	72	75.4	77	2.08%
<i>Nb</i>	0	0	0	0.00%

TABLE 4-6: Modelling the Sommes Cove granitic unit from the Cadillac Mountain Granite. All traces except Sr are within 5% error. This strongly suggests the Sommes Cove granitic unit is a fractionate from the CMG.

Ri/Rc=0.5	FJV-1a	95%	90%	80%	70%	FJV-21	Error
V	174	178.1	182.4	191.6	201.8	201	0.40%
Co	29	28.3	27.6	26.1	24.7	25	1.20%
Zr	135	150.6	166.9	202.3	241.8	244	0.90%
Rb	25	28	31	38	46	0	-
Sr	22	229	265	250	267	253	5.53%
Y	14	16.3	18.8	24.1	30	32	6.25%
Nb	9	9	10	11	11	17	35.29%

TABLE 4-7: Ri/Rc = mixing rate/fractionation rate. FJV-21=Chilled Gabbro.

The chilled gabbro models well as a fractionate from the basaltic dike with partial granite mixing. The Rb ppm for FJV-21 is unusual as compared to other chilled margins from MDI. Most have values of approximately 40 ppm.

The best modelling results for this unit are shown in Table 4-7. Pure fractional crystallization from FJV-1a does not produce the trace element signature, so the felsic end-member is introduced. The ratio of mixing rate:fractionation rate is 1:2, and the fractionating phases are a typical fractionating mafic mineral assemblage: 70% plagioclase, 20% olivine, 5% clinopyroxene, and 5% oxides. A reasonable match is achieved with a 70% fractionate of FJV-1a, the mafic end-member. The modelled and actual concentrations of 5 trace elements are within 7%. Nb is significantly different, although the increasing trend for the element is appropriate. Rb, however, is problematic; either the measured concentration for the gabbro (0 ppm) is incorrect, or the chill did not fractionate from the basaltic dike magma. Published Rb concentrations for other MDI chilled gabbros range from 17 to 75 ppm, a range inclusive of the modelled 46 ppm. Therefore, from this data it is reasonable to suggest FJV-21 could be the result of fractionation from the basaltic dike magma with an incorporated felsic component.

Coarse Gabbro

Petrographic textures of the coarse gabbro sample, FJV-8, are much more complicated than FJV-21, the chilled gabbro. Although the mineral assemblages are similar, glomerophyrocysts are more common, and the range of crystal size and development is very broad. Plagioclase has two populations: small, equant, and anhedral and large, euhedral laths. Pyroxene, amphibole, and biotite also have two grain size populations, and interstitial quartz is ubiquitous. All of these factors suggest a more complicated crystallization history, possibly with mixing playing a more important role than in the chilled gabbro.

TABLE 4-8

Ri/Rc=mixing rate/fractionation rate. FJV-8=Coarse Gabbro

Ri/Rc=0.5	FJV-1a	95%	80%	73%	FJV-8	Error
V	174	178.1	191.6	198.2	140	41.57%
Co	29	28.3	26.1	25.2	27	6.67%
Zr	135	150.6	202.3	227.9	228	0.04%
Rb	25	28	38	43	47	8.51%
Sr	222	229	250	261	262	0.38%
Y	14	16.3	24.1	27.9	37	24.59%
Nb	9	9	11	11	15	26.67%

TABLE 4-9

Ri/Rc=mixing rate/fractionation rate. Poor match for trace elements.

Ri/Rc=1.83	FJV-1a	95%	80%	70%	FJV-8	Error
V	174	167.2	149.7	140.1	140	0.07%
Co	29	26.5	20.7	17.8	27	34.07%
Zr	135	171.5	265.1	317	228	39.04%
Rb	25	33	54	65	47	38.30%
Sr	222	218	207	201	262	23.28%
Y	14	20.2	36.1	45	37	21.62%
Nb	9	11	14	16	15	6.67%

TABLE 4-10

Ri/Rc=mixing rate/fractionation rate. FJV-8=Coarse Gabbro

Ri/Rc=5.0	FJV-1a	95%	94%	FJV-8	Error
V	174	146	140	140	0.00%
Co	29	23.1	21.8	27	19.26%
Zr	135	211.9	228.7	228	0.31%
Rb	25	43	47	47	0.00%
Sr	222	197	192	262	26.72%
Y	14	27.7	30.7	37	17.03%
Nb	9	13	13	15	13.33%

These tables illustrate three different attempts to model FJV-8.

Table 4-10 may be the best model, as the high degrees of fractionation proposed by the other two models (~30%) would most likely alter the major element chemistry inappropriately for FJV-8.

For modelling, the same end-members and fractionating phases were used for the coarse gabbro. Several different scenarios produce this unit with equal success, each with a different ratio for mixing rate:fractionation rate. Three tables (4-8, 4-9, and 4-10) summarize these different possibilities.

Table 4-8 uses an equal mixing:fractionation ratio to that used for modelling the chilled gabbro: 1:2. Less of the mafic magma must be fractionated, however, to approximate the coarse gabbro: 27% vs. 30%. Four of the seven trace elements agree within 10%. Although there is a 26.67% error for Nb, its concentration agrees to within 4 ppm, well below the accuracy of the XRF. Tables 4-9 and 4-10 increase the role of mixing; table 4-10 uses a ratio of 5 to 1. Here, however, only 6% of the mafic end-member fractionates before a best match is reached. Again, four of seven traces agree to within 10%.

Determining which of these models is more likely is problematic. Petrographic textures suggest mixing plays a more important role in the coarser gabbros, though the high degree of mechanical mixing suggested by table 4-10 seems petrologically absurd. Table 4-8, however, models FJV-8 with less fractional crystallization than FJV-21 (27% vs. 30%), implying the coarse gabbro is derived from a more primitive liquid, a possibility no more likely than a high degree of mechanical mixing. This implication also disagrees with major oxide concentrations; the chilled gabbro has higher concentrations of all mafic oxides, and is lower in SiO_2 and K_2O . The chilled gabbro *should* be more representative of the primitive liquid than the coarse gabbro. Also, 30% fractionation would most likely result in inappropriate major element chemistries. Therefore, the remaining conclusion is that the simplicity of the model is inadequate for the complexity of this system.

Heterogeneous Quartz Monzonite

Using the same end-member chemistries, an attempt to model FJV-23, a heterogeneous intermediate unit, yields some revealing results. Pure fractional crystallization of the chilled gabbro, with no incorporation of the felsic end-member, could not have produced this unit as several of the trace element concentrations trended in the wrong direction; i.e. V, Zr, Rb, and Sr all increased in concentration with *increased* fractional crystallization and to produce FJV-23 they need to *decrease*. By mixing in the felsic end-member at a roughly equal rate to fractionation, a more reasonable estimation of the unit is attained. Table 4-11 summarizes the results.

Partial Melting

A spreadsheet similar the one used above was used in an attempt to produce granitic unit trace element chemistries by partially melting gabbro. The same seven trace elements were used. Models consistently indicated that phenomenally large volumes of the gabbro, greater than 70%, must be melted to produce the high concentrations of Zr, Nb, and Y in the granitic units. This seems unlikely, and is inconsistent with field relations. Also, modelled Co, Sr and V concentrations increase, where as they decrease in the actual units. Of the seven traces, only Rb modelled in a manner consistent with actual chemistries.

Modelling Conclusions

Using a highly simplistic model for a highly complex system provides only moderate enlightenment, though some rough conclusions may be drawn:

- Partial melting cannot produce the granite from the gabbro.

Ri/Rc=1.1	1.00	0.95	0.90	0.80	0.70	FJV-23	Error
<i>V</i>	174	173	172	170	168.1	168	0.05%
<i>Co</i>	29	27.7	26.4	24	21.9	27	18.99%
<i>Zr</i>	135	160.3	185.4	234.7	282.9	228	24.08%
<i>Rb</i>	25	30	36	46	56	35	60.00%
<i>Sr</i>	222	224	225	228	231	243	4.94%
<i>Y</i>	14	18.1	22.2	30.3	38.1	40	4.75%
<i>Nb</i>	9	10	11	12	14	16	12.50%

TABLE 4-11: Heterogeneous diorite is modelled with 70% fractionation from the basaltic dike, and a high degree of mixing with granite.
 Ri/Rc = mixing rate / fractionation rate.

- The granitic unit in Sommes Cove is a reasonable fractionate of the Cadillac Mountain Granite.

- Trace element signatures suggest pure fractional crystallization of the likely mafic end-member is inadequate to produce coarse gabbroic to intermediate units.

- Even fine-grained gabbroic units may have incorporated felsic liquid during crystallization, since models require mixing in addition to fractional crystallization.

CHAPTER FIVE

DISCUSSION and CONCLUSIONS

IGNEOUS LAYERING

The complexity of the layered gabbro-diorite unit of Mount Desert Island defies traditional interpretation using just the common igneous mechanisms of partial melting, fractional crystallization, and temporally discreet magmatic episodes. Mineralogy, petrographic textures, and geochemical data do not reveal classic partial melting or fractional crystallization processes, and tectonic classifications are ambiguous at best. As a result, Mount Desert's layered gabbro-diorite prompted the creative magma mixing interpretation of R.A. WIEBE, whose model's applicability to Sommes Cove is evaluated below. To better understand his reasoning, it is helpful to first consider more traditional interpretations of layered igneous suites.

Magmatic Differentiation Suites

The Skaergaard Intrusion

Many layered igneous series display units with progressive degrees of fractional crystallization, for instance, the Eocene Skaergaard Intrusion of East Greenland. This intrusion sets the standard for classic magmatic differentiation suites (MCBIRNEY, 1993). The simplified sequence consists of two layered series, the Layered Series and the Upper Border Series (MCBIRNEY, 1993; IRVINE, 1987). The Layered Series, at the base of the intrusion, is a 2,500 meter package of progressively more evolved layers: olivine rich units yield upsection to pyroxene-bearing and eventually granophyric rocks. The Upper Border Series crystallized from the top of the intrusion downward and displays a similar progression of units. It is,

however, more plagioclase rich, a result of buoyant laths rising in the chamber. The two series meet at the "Sandwich Zone," where the most differentiated magmas collected; rocks here are rich in granophyre, alkali feldspar, and zircon. The two series are (relatively) easily explained by a classic differentiation progression of fractional crystallization.

Other magmatic episodes on Greenland display evidence of differentiation through progressive accumulation of fractionated minerals. South Greenland's Tugtutôq Younger Giant Dyke Complex has folded layers with increasing concentrations of minerals that follow Bowen's Reaction Series: plagioclase to olivine to clinopyroxene to alkali feldspar (UPTON, 1987). Adjacent to the Skaergaard, Lilloise Intrusion's cumulates are also folded in a manner similar to soft-sediment deformation (BROWN et al., 1987), and displays layering resultant from magmatic differentiation.

The layered sequences of these three intrusions have strikingly different textural field relations than the layered series of Sommes Cove. The Greenland layers are relatively discreet and planar, with good lateral continuity and little interlayer interactions. In contrast, Mount Desert Island layered sequences have irregular, cusate-lobate contacts with extensive interlayer mingling in the form of diapirs and pipes. Lateral continuity is poor, with layers of discreet pillows completely contained within more felsic matrices.

The Klokken Intrusion

Perhaps the most applicable differentiated layered pluton to this thesis is the Klokken intrusion near Ilimaussaq, South Greenland. This intrusion includes rocks from alkali gabbros to layered alkali feldspar syenites, although the two modes are rarely found in close association. The gabbro contacts the country rock and is the chilled primitive liquid, forming a distinct rim

around the circumference of the pluton. The bulk of the intrusion is the layered alkali feldspar syenites, with two distinct textures: 1) a laminated syenite, and 2) a coarser, granular syenite.

These two syenites form complexly intercalated layers with structures strongly reminiscent of the Mount Desert Island layered gabbro-diorites. Laminar syenite intrudes overlying granular syenite layers, forming "load pouches" at the base of the granular layer and "flame structures" in the laminar unit. As in Sommes Cove, the underlying unit has minerals laminated parallel to the cusate-lobate contact and flow into the "flames" or diapirs. Granular layers are sometimes desegregated, forming layers of discreet "pillow-like xenoliths" within the laminar syenite (PARSONS and BECKER, 1987).

Although the Klokken and the CMIC display similar field relations, they are not identical, and important distinctions exist between the two. First, the compositional variations within the Klokken's layered series is small, and the bulk chemistries between units are almost identical. Secondly, the concentric progression from gabbro to syenite is a simple fractional crystallization sequence. Finally, the layered syenites exhibit no evidence of thermal gradients between units, i.e. chilled margins; the Klokken formed under thermal equilibrium conditions (PARSONS and BECKER, 1987). All of these characteristics contrast with the Sommes Cove layered series. The Klokken's layered series is thought to have formed through magmatic differentiation processes, whereby granular syenite layers cooled against the upper margin of the chamber, periodically became unattached and descended upon the crystallizing syenites below, forming the macrorhythmic layering observed.

Magma Mixing

Newark Island Layered Intrusion (NILI)

Other layered intrusions are the result of comagmatic interaction of two or more compositionally contrasting liquids. The Newark Island Layered Intrusion (NILI) of Nain, Labrador is a Proterozoic member of the Nain Anorthosite Complex, and displays field and petrographic relationships strikingly similar to the layered gabbro-diorites of MDI (WIEBE, 1988). The NILI consists of two layered sequences: the Layered Series and the Hybrid Series. The Layered Series is a typical assemblage of progressively differentiated units, interspersed with periodic injections of additional magma. The compositional variation within the Layered Series is narrow.

The Hybrid Series, however, displays a wide compositional variation in a sequence of interlayered mafic and felsic cumulates with strongly chilled contacts between them. Compositions range from troctolites to hornblende diorites. Most mafic layers consist of desegregated pillows of chilled gabbro, 1 to 3 meters thick. Larger mafic layers have chilled, cusped-lobate basal contacts that grade upward to coarse gabbro and hybridized units. Quartz and potassium feldspar xenocrysts mantled by sodium plagioclase (rapakivi texture) suggest hybridization, as do the felsic assemblages of quartz, ksp, and sodic plagioclase within gabbroic units revealed by petrography. WIEBE considers the Hybrid Series the result of periodic infusions of felsic and mafic magmas that filled the chamber sufficiently to form cumulates, which then subsequently intermingled and hybridized.

The larger layers of mafic magma formed only basal chills, and grade upward for 10's and 100's of meters through hybridized units to granitic cumulates. The upper margin of the mafic influx was not a stable chill, but rather a steep thermal and compositional gradient that, as evidenced by

hybrid units, was the site for relatively vigorous convection and compositional diffusion. Petrographic evidence includes large biotites surrounded by pyroxene rims; WIEBE suggests the biotite crystallized near the upper mafic interface with water and potassium that diffused through the boundary, and were then carried down by convection into a more mafic environment where the pyroxene rims formed.

Isle Au Haut Igneous Complex

Very similar relationships to NILI occur on an island adjacent to MDI, off the southern coast of Maine. The Isle Au Haut Igneous Complex consists of a rhythmically-layered granite-gabbro-diorite suite, formed through magma mixing (CHAPMAN and RHODES, 1992). All of the characteristic comagmatic structures described above are here as well. Large, basally chilled gabbros grade upward through hybridized units to granitic cumulates; cuscate-lobate contacts are described as "load cast structures" (PETTIJOHN et al., 1974 in CHAPMAN and RHODES, 1992) similar to those described by PARSONS et al. (1987) in the Klokken intrusion. Also, individual gabbroic pillows with chilled rinds are found encased in dioritic matrices. Diapirs and pipes form perpendicular to layering; as these structures follow a decreasing gravitational gradient (i.e. vertically upwards), they provide evidence that the layers were originally horizontal, and evidence of the original up direction. The pipes become less common and more diffuse higher in the layer.

Relationships identical to the ones described above exist in the Pleasant Bay Layered Gabbro-Diorites, another member of the Coastal Maine Magmatic Province (WIEBE, 1993). It is interpreted to be the result of periodic infusions of basaltic magma into a granitic chamber, that mingled and mixed to varying degrees with the host liquid.

SOMMES COVE LAYERED SEQUENCE

Remarkable field and petrologic similarity with previously interpreted magma mixing localities adds credence to the theory that similar processes account for the Sommes Cove layered series. Field, petrographic, and geochemical data gathered during the current research strongly support WIEBE's model.

Data Interpretations

Field relations provide some of the strongest evidence for comagmatic interaction. Contacts between units are *relatively* indistinct, or "soft," contrasted with the sharp, angular contacts of the late stage basaltic and pegmatitic dikes. Soft contacts would more likely result from contemporaneous liquids, where diffusion and intermingling are possible, than temporally distinct episodes. Macroscopic kspar and quartz xenocrysts and microscopic felsic glomerphyrocrysts within near-contact mafic units indicate comingling; rapakivi textures suggest an increased mafic environment. Chilled gabbroic margins also imply a non-differentiation relationship; fractionation and liquid immiscibility are thermal equilibrium processes.

Flow lamination exists on both sides of the contact. Macroscopic hornblendes and biotites parallel to the contact indicate the felsic unit was liquid during contact emplacement. Similarly, microscopic high aspect ratio biotites within the chilled gabbro are also laminated. Both units, therefore, must have been liquid during contact formation.

Intermediate units exhibit strong evidence for hybridization. Rapakivi kspars are common, and petrographically, essentially all intermediate units have hybridized textures. Ubiquitous mafic and felsic gloms give these units a

patchy appearance. Abundant disequilibrium crystallization conditions are preserved. Embayed and partially resorbed plagioclase crystals exhibit strong normal zoning, and large kspars enclose small, anhedral mafic crystals such as hornblende, biotite, and plagioclase. Pyroxenes have thick amphibole reaction rims. The more mafic intermediate units, such as FJV-23, contain interstitial quartz in a disequilibrium, coarse mafic mineral assemblage. All of these factors imply rapidly changing thermal and compositional conditions, an expected consequence of hybridization.

In the two feldspar granitic unit (FJV-4) just below the irregular contact with the overlying single feldspar granite (FJV-3), amphibole surrounds biotite. This is inconsistent with a normal progression down Bowen's Reaction Series, where amphibole crystallizes before biotite. It is in agreement, however, with WIEBE's convection model. I suggest the contact between the two feldspar and single feldspar granites is the upper boundary of a large gabbroic layer, the basal chill of which is not seen in outcrop. The biotite crystallized at the boundary and was subsequently carried downward into a more mafic environment by convection, similar to the pyroxene-mantled biotites of the Newark Island Layered Intrusion. The two feldspar granite grades downward into more intermediate units; the transition to the overlying granite occurs within 2-3 centimeters, marked by the dramatic decrease in plagioclase and mafic phases.

Convection

Convection, resulting from the thermal gradient across the boundary, may also explain the presence of the large, single feldspar granite inclusion below the contact. This inclusion suggests something about the nature of the convection in the lower unit, although a complete consideration of all

involved rheological factors is beyond the scope of this paper. A form of free convection, resulting from the steep thermal gradient between the gabbroic and granitic liquids, could account for many of the observed textures. BRANDEIS and JAUPART (1986) used this style of convection when considering cooling affects through the roof of a magma chamber. Similar to roof cooling, gabbro injected below the colder granitic magma loses considerable heat up into the overlying liquid and begins crystallizing. This forms a layer of high density, partially crystalline gabbroic magma above hotter, less dense liquid. This creates a density inversion, and plumes of the dense layer fall. As the partially crystalline gabbroic liquid falls, it entrains some of the overlying granitic magma which becomes partially reassimilated and hybridized (Figure 5-1). This explains the patchy textures of glomerophyrocysts, disequilibrium conditions, intermediate chemical compositions, felsic xenocrysts, variable grain sizes, heterogeneous outcrops, and biotites surrounded by amphibole that characterize the hybridized units. The inclusion of overlying granite observed is considerably well preserved because it achieved neutral buoyancy a meter into the underlying unit, suggesting the underlying unit was largely crystalline. The inclusion was therefore relatively unassimilated, although there is partial comingling still evident. The heat from the underlying gabbro would drive another convection mechanism in the upper, granitic unit. It is this convection that WIEBE proposes carries desegregate portions of the gabbroic units up into the Cadillac Mountain Granite, forming enclaves. This style of convection would also destroy the chill margin at the top of the gabbro, while preserving the chill at the base of the unit which does not create a density inversion.

The Sommes Cove diapirs and pipes are another form of convection; the vertical movement of magma driven by buoyancy forces results from

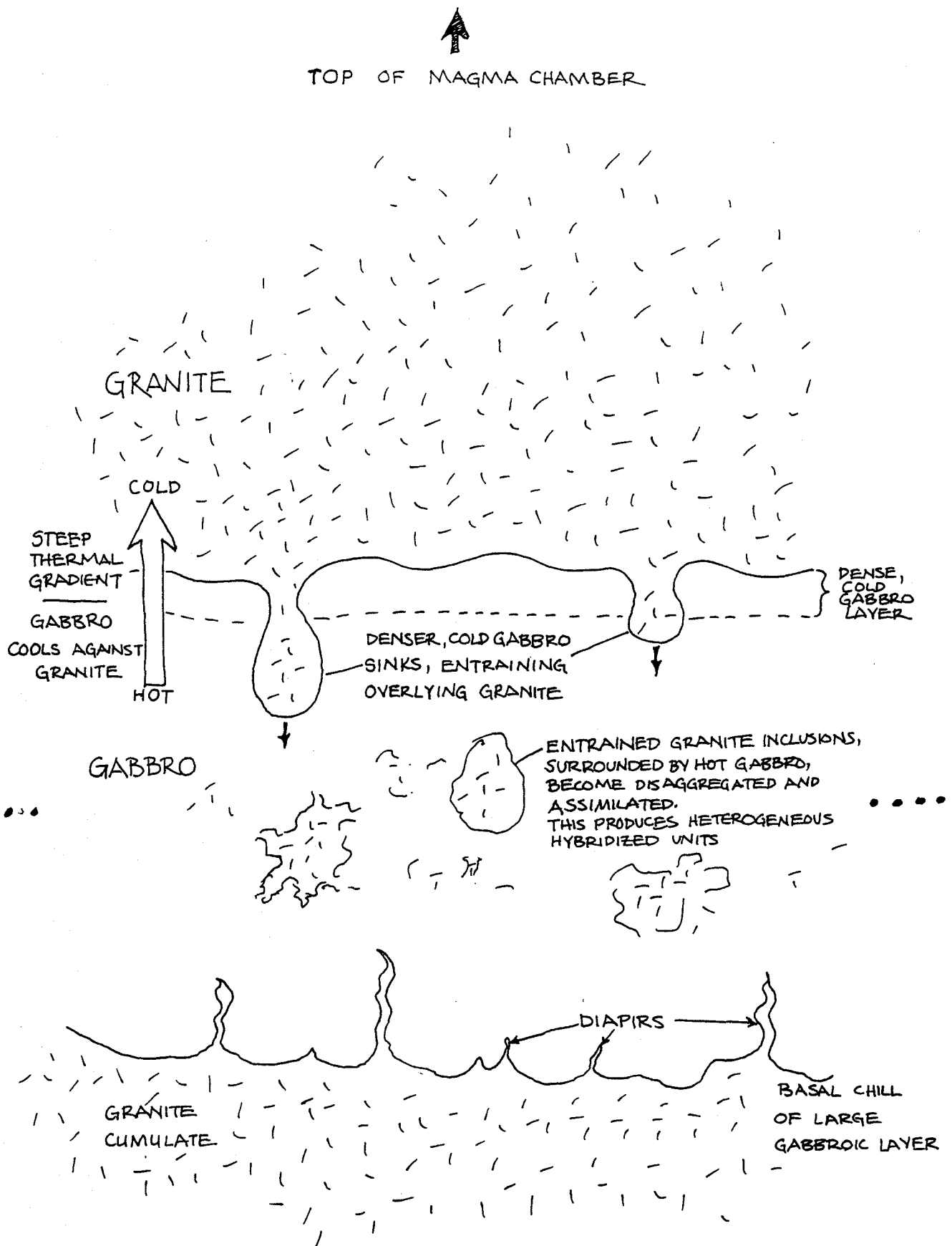


FIGURE 5-1: POSSIBLE MECHANISM FOR HYBRIDIZATION OF INTERMEDIATE UNITS, THROUGH CONVECTION.

density contrasts. Dense, chilled gabbroic layers overlie relatively fluid rich intermediate to granitic matrices. Similar to sedimentary diapirs, the felsic magma migrates laterally until a weakness in the overlying layer is breached and it can rise. This behavior laminates and segregates the elongate hornblendes and biotites in the felsic diapirs.

Fluid concentrations at the contact are strongly supported by the coarse quartz and alkali feldspar crystals here in the felsic unit. Biotite and hornblende, both hydrous phases, are enriched at the contact, in both the felsic and mafic units. Enrichment of the chilled gabbro probably results from the hydrous alteration as water diffuses across the contact. Volatiles may concentrate at the contact because the crystallized, chilled gabbro is relatively resistant to fluid movement as compared to the still liquid felsic matrix.

Geochemistry and Mixing

Geochemical evidence provides some support for magma mixing in Sommes Cove. The partial melting model does not provide a viable explanation for the observed chemistries, particularly when volumetric relationships are considered. Modeling also suggests fractional crystallization is inadequate to produce the variety of units observed; incorporation of a felsic end-member models trace element signatures more successfully.

Oxides plotted against silica reveal linear relationships, a pattern suggestive of end-member mixing (MCBIRNEY, 1993). Non-linear relationships, however, do not necessarily forbid a mixing model. Recent evidence suggests non-linear trends may result due to differing diffusivities of different elements (LESHER, 1990 in CHAPMAN and RHODES, 1992).

Layering

The regular layering characteristic of MDI's layered gabbro-diorites is seen in other mixed plutons of the Coastal Maine Magmatic Province, such as Isle Au Haut and Pleasant Bay. The progression from the basal, gabbroic chill through coarse, heterogeneous "diorite" to granite has been dubbed a "macrorhythmic unit" by WIEBE (1992) and CHAPMAN and RHODES (1992). (PARSONS et al. (1987) also used "macrorhythmic" to describe the layered syenites of the Klokken intrusion.) The layered gabbro-diorites of MDI contains hundreds of macrorhythmic units (WIEBE, 1993), the result of many periods of basaltic infusion into the CMIC chamber.

The layered sequence of Sommes Cove is the result of periodic infusions of basaltic magma into the floor of the Cadillac Mountain Granite magma chamber, and represents two incomplete macrorhythmic units. The upper two thirds of the sequence is the lower portion of a rhythmic unit, where the large, basal chill at 25 meters (Figure 2-2) is the base of the unit. The chilled gabbro grades upward to a hybridized unit at the top of the section. In the simplest scenario, one would expect the uppermost unit to have intermediate chemistry. However, an analysis of compatible and incompatible elements with height (Figures 4-7 through 4-12) shows a surprising increase in mafic character at the top of the section. This could result from a large mafic replenishment, unseen because of the paucity of outcrop immediately down section (Figure 2-2). The lower portion of the Sommes Cove sequence represents the upper portion of a macrorhythmic unit, where hybridized "diorite" grades to granite.

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APPENDIX

Unadjusted, raw XRF data for all Sommes Cove units.

Sample #	FJV-1a	FJV-8	FJV-14	FJV-21	FJV-4	FJV-5	FJV-23	FJV-27	FJV-3	FJV-6	FJV-7	FJV-15
Type	Basalt Dike	Coarse Gab	Composite Dike Basalt	Pillow Chill	Transition Di	Diorite	Diorite	Diorite	Transition Gr	Granite	Intermed Gr	Composite Aplite
Method	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF	XRF
SiO ₂	46.28	53.10	52.55	48.91	61.78	61.69	52.98	45.85	71.36	70.47	65.71	70.93
TiO ₂	1.25	1.76	0.50	2.44	0.61	0.69	2.07	1.81	0.34	0.36	0.52	0.29
Al ₂ O ₃	15.59	15.08	15.64	15.05	13.59	14.22	14.41	15.94	12.57	12.73	13.51	13.49
Fe ₂ O ₃	-	-	-	-	-	-	-	-	-	-	-	-
FeO	9.23	9.35	6.03	12.56	4.70	5.41	11.06	10.82	2.63	3.16	3.99	2.19
MnO	0.16	0.15	0.09	0.26	0.09	0.09	0.17	0.21	0.03	0.06	0.07	0.03
MgO	7.40	3.98	6.50	4.67	2.41	2.68	3.93	7.46	0.28	0.25	1.90	0.31
CaO	9.74	6.74	6.87	7.31	3.76	4.27	7.08	8.42	1.19	1.26	3.23	1.76
Na ₂ O	2.32	3.42	9.36	3.51	3.19	3.37	2.80	2.69	2.78	3.35	3.75	3.20
K ₂ O	0.58	1.50	1.64	1.03	2.79	2.62	1.60	0.91	4.61	4.34	1.47	3.94
P ₂ O ₅	0.11	0.26	0.06	0.35	0.09	0.11	0.25	0.25	0.04	0.04	0.08	0.05
LOI	-	-	-	-	-	-	-	-	-	-	-	-
TOTAL	92.65	95.34	99.24	96.08	93.02	95.15	96.35	94.36	95.82	96.02	94.23	96.19