Geology of the Plutonic and Hypabyssal Rocks of the Betts Cove Ophiolite Complex, Newfoundland

A thesis presented to the Faculty
of the State University of New York
at Albany
in partial fulfillment of the requirements
for the degree of
Master of Science

College of Science and Mathematics
Department of Geological Sciences

Bruce D. Idleman

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ABSTRACT

The Betts Cove ophiolite complex lies within the Dunnage Zone island arc terrain of central Newfoundland. It forms the base of the lower Ordovician Snooks Arm Group, which consists of mafic igneous rocks of the ophiolite and a thick sequence of volcanic and volcaniclastic rocks which conformably overlies it. The Snooks Arm Group is unconformably overlain by sub-aerial sediments and volcanics of the presumed Silurian Cape St. John Group.

The base of the ophiolite complex consists predominantly of ultramafic rocks. These are interlayered on a variety of scales, and show mesoscopic igneous structures which suggest that they were produced by magma chamber processes. They consist largely of olivine, orthopyroxene, and clinopyroxene, with minor plagioclase and chromite. These phases are generally quite altered, but original igneous textures are well-preserved in most samples.

A thin sequence of interlayered ultramafic and gabbroic rocks overlies these layered ultramafic rocks. This sequence is similar to the underlying one, but contains a significantly greater proportion of gabbroic rocks. Most of the mesoscopic features of these interlayered rocks are similar to those of the layered ultramafic rocks. In some places interlayered rocks pass upward into a thin zone of homogeneous gabbro, which is largely devoid of compositional variation, igneous layering, and other mesoscopic features. This gabbro consists primarily of variably altered plagioclase, clinopyroxene, orthopyroxene and rare olivine.

A sheeted diabase dike complex overlies the plutonic portion of

the ophiolite. In some places the contact between the dikes and the plutonic rocks is quite sharp, while in others dikes related to the sheeted complex extend downward as far as the upper portion of the layered ultramafic sequence. The sheeted complex consists almost entirely of altered diabase and picritic diabase dikes, with rare screens of gabbroic and ultramafic plutonic lithologies.

The ophiolite is capped by altered, basic volcanic rocks, occurring as pillows, massive flows, and volcanic breccia. Dikes of the sheeted complex extend upward into these volcanics in places.

Many of the oroginal petrologic and structural characteristics of the Betts Cove ophiolite have been obscured by deformation and metamorphism, which occurred at the same time as or soon after the formation of the ophiolite. Despite this, detailed mapping has shown that the ophiolite consists of a conformable sequence of igneous rocks similar to those seen in other ophiolite complexes. It differs somewhat from many ophiolites, however, in that the thickness of its gabbroic sequence is quite small. Field relationships, augmented by geochemical and petrologic data, suggest that the ophiolite complex was produced from a picritic primitive melt by igneous processes occurring within and adjacent to a high-level, sill-like magma chamber. Structural relationships observed within the complex provide some constraints for the size and geometry of this chamber.

Regional relationships and geochemical data suggest that the Betts Cove ophiolite was formed during Early Ordovician time as a marginal or rear-arc basin above an east-dipping subduction zone.

ACKNOWLEDGEMENTS

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Ms. Diane Paton patiently typed the final draft of this thesis, and provided indispensable help in solving various logistical problems which cropped up from time to time during the course of my research work.

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CHAPTER I

INTRODUCTION

A. Purpose

The Betts Cove ophiolite complex is located on the east coast of the Burlington Peninsula in north-central Newfoundland. It forms the southern portion of a 20 km long arcuate belt of ophiolitic rocks outcropping between the coastal communities of Tilt Cove and Nippers Harbour. The complex consists, from bottom to top, of layered ultramafic rocks, layered and homogeneous gabbros, sheeted diabase dikes, and mafic pillow lavas. It represents a nearly complete ophiolite and as such is a presumed remnant of oceanic crust and mantle (Dewey and Bird, 1971; Church and Stevens, 1971; Church, 1972; Conference Participants, 1972). Overlying the ophiolite complex is a thick sequence of mafic volcanic rocks and predominantly volcaniclastic sediments. Together, the ophiolitic rocks and overlying sequence comprise the lower Ordovician Snooks Arm Group (Upadhyay *et al.*, 1971).

At the time this study was undertaken several descriptions and maps of the Betts Cove ophiolite were available. A map of the Nippers Harbour area compiled by Neale (1958) showed the basic distribution of lithologies within the ophiolite, but at a scale of 1:63,360 was not sufficiently detailed to show much internal structure. Descriptions and maps by Upadhyay *et al.* (1971) and Upadhyay (1973) described the ophiolite as a conformable sequence of igneous rocks derived from a single parent magma. The lowest exposed rocks of the complex were described as layered cumulate ultramafics, passing gradationally upwards into a thin gabbroic member with a clinopyroxenite-rich zone at its base. Sheeted diabase dikes of the next higher unit were described as gradationally overlying the gabbro, with mafic pillow lavas capping the sequence. Descriptions of the lithologic sequence seen in the ophiolite by Riccio (1972) were similar, but he interpreted the contact between the ultramafic and gabbroic members as a sharp discontinuity, with rocks of the gabbroic member intrusive into those of the ultramafic member. He suggested that these two members were derived from separate parent magmas.

The object of this study was to examine selected portions of the Betts Cove ophiolite in order to determine structural and lithologic relationships within its plutonic section and to clarify ambiguities resulting from differences in previous interpretations. It was hoped to use this data to place constraints upon the processes involved in the formation of the Betts Cove ophiolite, and to test previously proposed models for ophiolite generation.

B. Previous Work

A multitude of geologists have conducted investigations in the Betts Cove region during the past 120 years. The summary presented here is by no means a complete account of all geological investigations in this area, but lists those that have made the most significant contributions to the topics discussed in this thesis.

Alexander Murray was the first geologist to study the Betts Cove region. As a geologist for the Newfoundland Geological Survey from 1864 to 1881 he and various colleagues made several excursions into the area. The results of these were summarized by Murray and Howley (1881).

The first detailed accounts of the geology of the area were provided by Snelgrove (1931). He described various igneous relationships occurring in the vicinity of Betts Cove and concluded that the ultramafic rocks of the region had been intruded into the overlying volcanic and sedimentary rocks, which he termed the Snooks Arm Group. He also found graptolites of Arenig age in Snooks Arm sediments at one locality.

Subsequent researchers also proposed an intrusive origin for the ultramafic rocks of the area. Baird (1951) described these as concordant plutons, and based on field relationships suggested that they were post-lower Ordovician but pre-Devonian in age. Neale (1957) presented a similar interpretation, and later proposed an intrusive origin for all ultramafic rocks of the Burlington Peninsula (Neale and Kennedy, 1967).

Stevens et al. (1969) were the first to apply the term "ophiolite" to ultramafic-mafic igneous complexes in Newfoundland. Shortly thereafter a number of researchers suggested that these complexes (including Betts Cove) might represent oceanic crust and mantle (Stevens, 1970; Church and Stevens, 1971; Dewey and Bird, 1971). Kennedy and Phillips (1971) proposed possible ages for the ophiolites of the Burlington Peninsula based on structural relationships, and inferred an Ordovician age for the ophiolite at Betts Cove.

The interpretation of Newfoundland ophiolites as oceanic crust led to renewed interest in Betts Cove and prompted several new and more detailed investigations. Preliminary data and maps from one such investigation were presented by Upadhyay et al. (1971). They suggested a marginal basin origin for the Betts Cove ophiolite and proposed that it be included within the Snooks Arm Group. This was followed by more detailed descriptions and maps of the entire Snooks Arm Group (Upadhyay, 1973), and a note on sulfide mineralization in the Betts Cove ophiolite

(Upadhyay and Strong, 1973). A similar moderately detailed study of the ophiolite complex was conducted by Riccio (1972).

Petrologic and geochemical studies of the ophiolitic rocks of the Snooks Arm Group have been described by Upadhyay (1976, 1978), Coish (1977a,b and 1979), and Coish and Church (1978, 1979).

C. Physiography

The topography in the vicinity of Betts Cove forms a highly dissected plateau with a maximum elevation of about 180 m, which terminates along the coast in many places in steep to near vertical cliffs. Inland this plateau is cut by numerous steep-walled valleys within which the major streams of the area flow. These commonly have steep gradients and numerous falls and rapids, forming part of a young, poorly integrated drainage system. Deep fiord-like embayments occur where steep-sided valleys intersect the coast, the most prominent of these being Snooks Arm and Betts Cove. The topography and the abundance of such features as erratics, striated and polished outcrop surfaces, and scattered till deposits suggests a glacial origin for most of the landforms of the area. The resistance of the underlying bedrock appears to have had considerable control over topography, as most large valleys are underlain by serpentinized ultramafic rocks or occur along fault zones.

The extent of outcrop in the area is variable and depends upon the type of underlying bedrock. Areas underlain by ultramafic and gabbroic rocks have poor soil cover, little or no vegetation, and generally excellent outcrop which averages 60 to 100% in most places. Vegetation is somewhat more abundant in the sheeted dike unit, though outcrop is still plentiful. Areas underlain by volcanic and sedimentary rocks are usually heavily vegetated and commonly support softwood forests. Outcrop in these areas is sparse, except along the coast where the exposure is excellent.

The easiest access to the region is by boat, as excellent places to land exist in most of the small coves along the coast. Landings on the exposed portions of the coast are generally difficult because of rugged shoreline topography and rough seas, but most of the superb coastal exposures can be examined from a boat on calm days. Several networks of trails exist in the region, simplifying travel in forested areas. Parts of these are partially or totally obscured by vegetation, but in many places they can be negotiated without excessive difficulty.

D. Field Work

Most of the field work for this study was accomplished during the period from June through September, 1978. The area was revisited for one week during July, 1979, to recheck key relationships.

Portions of the area judged most worthy of detailed examination were selected after a reconnaissance study of the ophiolite complex by the author in June, 1978, made with the aid of information from previous studies (Neale, 1958; Upadhyay *et al.*, 1971; Upadhyay, 1973). Effort was made to examine every outcrop in detail within the selected map areas. Enlargements of aerial photographs at an approximate scale of 1:3,200 were used with mylar overlays to record outcrop locations.

Access to the area was by small boat from Nippers Harbour, which is about 7 km southwest of Betts Cove. An open grassy area adjacent to a beach at the end of Betts Cove was used as a campsite. This site provided protection and safe anchorage for a small boat under most weather conditions.

CHAPTER II

REGIONAL GEOLOGY

The island of Newfoundland has been the subject of considerable geological scrutiny ever since Wilson (1966) pointed out that remnants of an ancient ocean basin which had opened and subsequently closed during Paleozoic times were preserved there. This oceanic domain lies between two platform sequences with continental affinities, the Western Platform on the west coast of the island, and the Avalon Platform to the east.

Advances in plate tectonic theory during the past fifteen years have added immeasurably to the understanding of mountain belt evolution. Bird and Dewey (1970) and Dewey and Bird (1971) were the first to utilize plate tectonic concepts in an attempt to unravel the geological history of the Appalachians in general, and Newfoundland in particular. Their work has been followed by a number of recent studies utilizing a larger and more current data base (Williams et al., 1974; Kennedy, 1975; Williams, 1979).

Newfoundland can be divided into four main tectonic zones (Williams, 1979) (figure 1). The Humber Zone, located along the west coast of the island, consists of an east-facing, Cambro-Ordovician continental margin sequence underlain by continental basement of Grenville age (1000 m.y.). Shelf sediments unconformably overlying this basement have been overriden by allochthonous continental rise sediments transported from the east during the Medial Ordovician. Structurally overlying the rise sequence are several large, well-preserved ophiolite complexes, the Bay of Islands and Hare Bay ophiolites.

To the east lies the Dunnage Zone, a complex assemblage of rocks

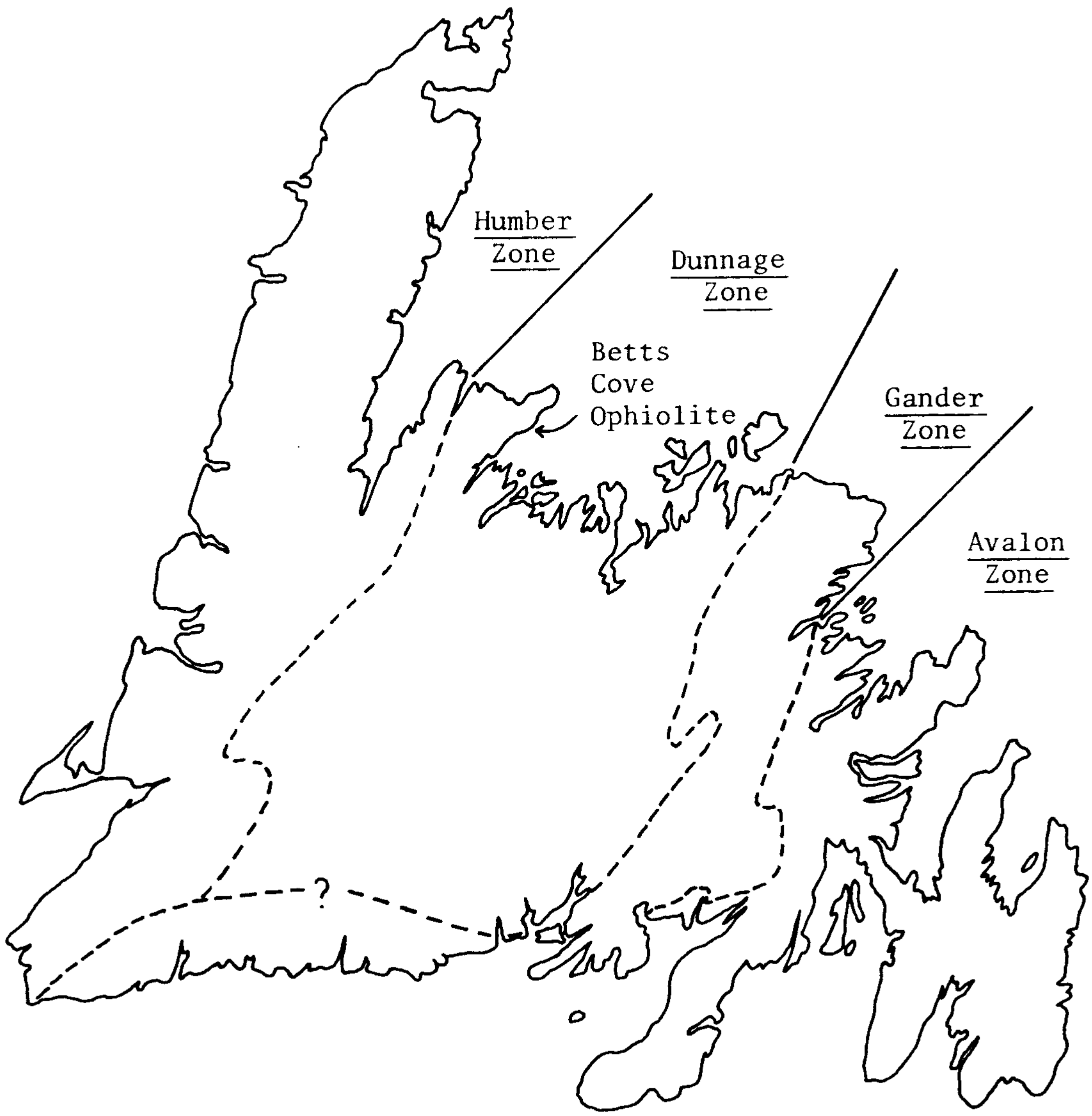


Figure 1

Tectonic zonation of Newfoundland (after Williams, 1979).

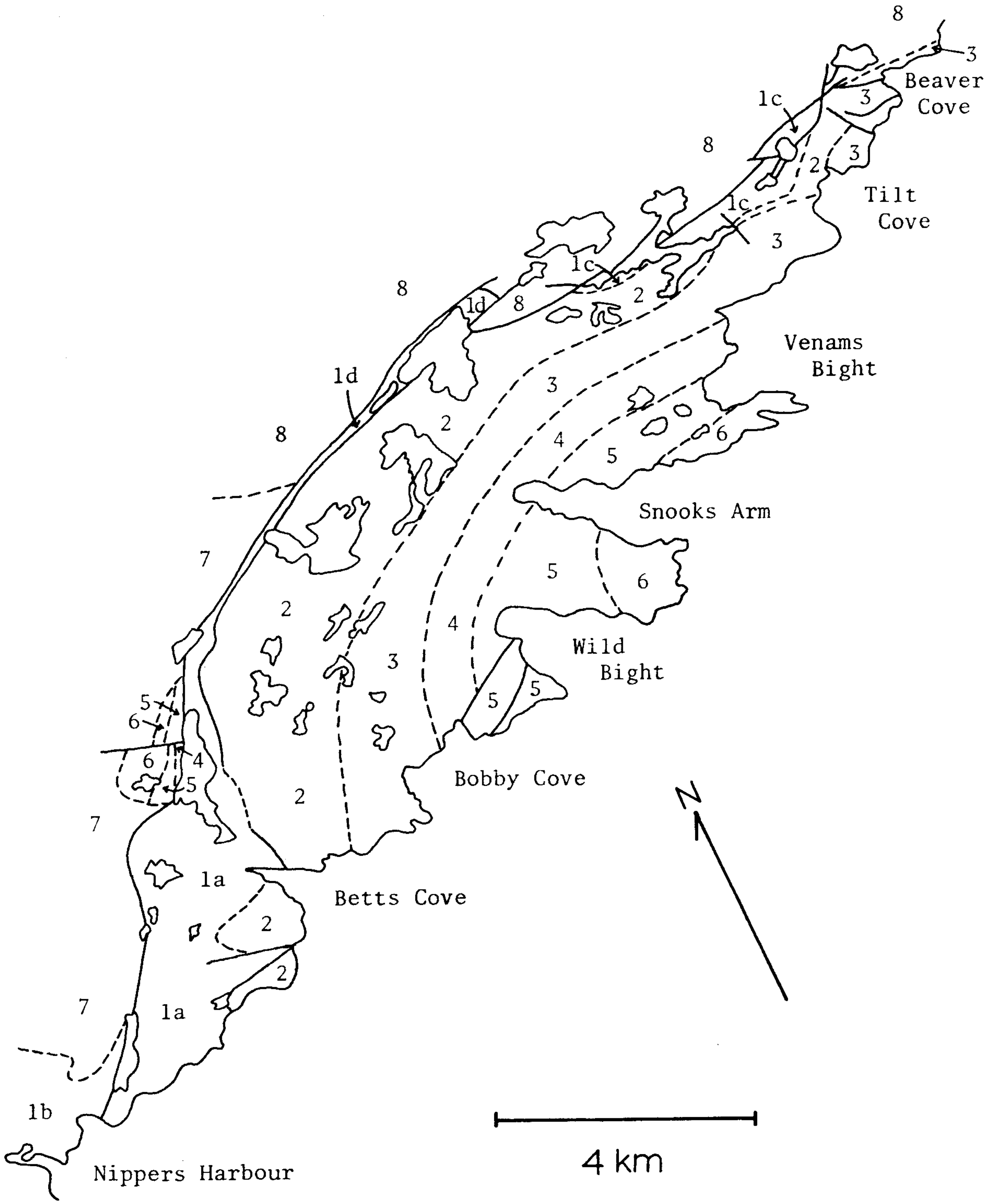
formed in an island-arc environment and which apparently overlie an ophiolitic basement. The Early Ordovician of the Dunnage Zone is represented primarily by subduction-related plutonic, volcanic, and volcaniclastic rocks. A cessation of volcanism appears to have occurred during the Caradocian. This was followed by an influx of westerly derived detrital sediments believed to have been produced from the erosion of allochthonous continental rise sediments and ophiolites being thrust to the west over the Humber Zone continental margin (Nelson and Casey, 1979). Small, generally highly dismembered ophiolites occur throughout the Dunnage Zone.

The Gander Zone consists predominantly of high-grade, complexly deformed metaclastic rocks which presumably represent a west-facing continental margin formed adjacent to the Avalon Zone platform, from which it is now separated by the Dover Fault. The Avalon Zone itself consists of shallow-water continental sediments and volcanic rocks of upper Precambrian age, which are locally overlain by Cambrian to lower Ordovician sediments.

The Betts Cove ophiolite lies within the Dunnage Zone of the Newfoundland Appalachians (figure 1). It forms the base of the lower Ordovician Snooks Arm Group (Upadhyay, 1973), and is described in detail in subsequent portions of this thesis. The northern and southern extensions of the Betts Cove ophiolite are generally referred to as the Tilt Cove and Nippers Harbour ophiolites, respectively. Conformably overlying the Betts Cove ophiolite is a sequence of mafic volcanic and volcaniclastic rocks which has been divided into four units by Upadhyay (1973) (figure 2). Lowermost of these is the Bobby Cove Formation (500 m thick), consisting of volcaniclastic sandstone, volcanic breccia, chert, and argillite. This is overlain by the Venams

Figure 2

Geologic map of the Nippers Harbour - Tilt Cove area (after DeGrace et al., 1976). Legend: Snooks Arm Group (1-6): 1a-Betts Cove ophiolite plutonic and hypabyssal rocks, 1b-Nippers Harbour ophiolite plutonic and hypabyssal rocks, 1c-Tilt Cove ophiolite plutonic and hypabyssal rocks, 1d-Highly deformed and altered ophiolitic rocks, 2-Ophiolitic volcanic rocks, 3-Bobby Cove Formation, 4- Venams Bight Basalt, 5-Balsam Bud Cove Formation, 6-Round Harbour Basalt; 7-Quartz-feldspar porphyry, 8-Cape St. John Group. Solid lines are faults, dashed lines are lithologic contacts.


8
3
Beaver
Cove
1c
3
8
3
2
Tilt
Cove
1c
3
8
1c
2
1d
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Venams
Bight
1d
3
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8
4
5
6
Snooks Arm
7
5
6
2
4
3
Wild
Bight
5
5
5
6
4
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5
Bobby Cove
2
7
N
1a
Betts Cove
2
2
7
1a
1b
Nippers Harbour
4 km

Bight Basalt (500 m thick), consisting largely of pillow lava and volcanic breccia, with minor sediments. Above this is another sedimentary unit, the Balsam Bud Cove Formation (750 m thick), which is similar in most respects to the Bobby Cove Formation. Capping the sequence is the Round Harbour Basalt (1000 m thick), another predominantly volcanic unit.

The Snooks Arm Group is in fault contact with rocks occurring to the west of it in most places. In the north it lies adjacent to the Cape St. John Group, a 3500 m thick sequence of sub-aerial calc-alkaline volcanic and sedimentary rocks of presumed Silurian age (DeGrace et al., 1976). Although in fault contact with the Snooks Arm Group in most places, the Cape St. John Group has been shown to unconformably overlie Snooks Arm sediments near Beaver Cove by Neale et al. (1975). In the southern portion of its exposure rocks of the Snooks Arm Group border on a large intrusive body of quartz-feldspar porphyry. The contact between the two is again faulted in most places, but the porphyry contains numerous large xenoliths of altered ultramafic rock, and has locally been shown to intrude plutonic rocks of the Betts Cove ophiolite (Upadhyay, 1973). This porphyry has been tenatively correlated with the nearby Cape Brule Porphyry, which is exposed to the northwest (DeGrace et al., 1976).

CHAPTER III

FIELD RELATIONSHIPS

A. Introduction

Field work conducted during this study was directed toward determining the lithologic and structural characteristics of the plutonic and hypabyssal portion of the Betts Cove ophiolite complex. Initial reconnaissance work was carried out over most of the complex to aid in the selection of areas for detailed study. The results of this reconnaissance mapping, along with data from Upadhyay (1973), appear on plate 1. Detailed mapping in a number of small areas shown on plate 2 provided the source for most of the descriptions presented in this chapter. Plate 3 depicts the locations of outcrops examined in detail during the course of the study.

The plutonic and hypabyssal portion of the Betts Cove ophiolite occurs as a series of structurally bounded blocks which comprise most of the western half of the complex. Five major blocks exist within the area shown on plate 2. These are referred to in this and subsequent chapters as areas A, B, C, D, and E (Figure 3). These areas are bounded by steep faults in most places and contain more or less intact sections of the ophiolite's plutonic and hypabyssal sequence. Descriptions of the general lithologic relationships occurring within this sequence and presented here were compiled primarily from observations made in areas A through D, as these contain the best-exposed and most intact sections of these rocks. Area E is structurally quite complex and is discussed separately, as observations made in this area are more difficult to interpret.

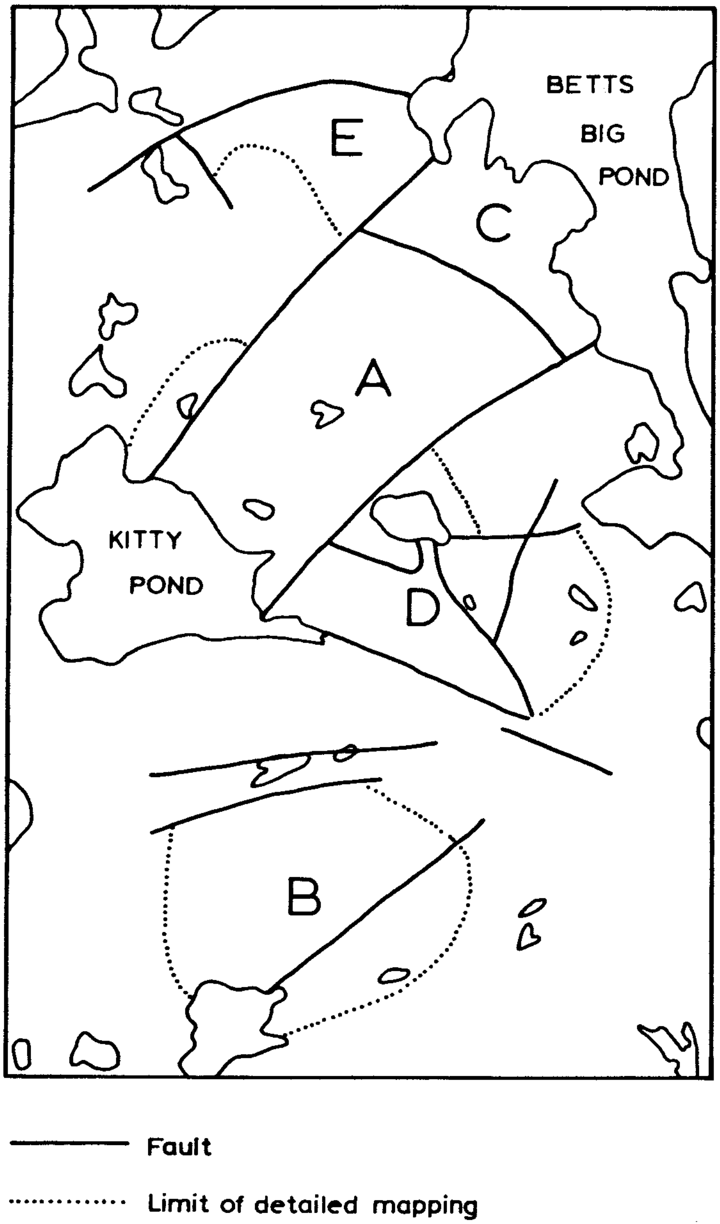


Figure 3

Location of map areas referred to in text.

The plutonic and hypabyssal rocks of the ophiolite generally occur as a continuous and gradational sequence of rock types. Sharp lithologic contacts between distinct units composed of vastly differing rock types are almost never seen. The gradational nature of this sequence causes complications in mapping, as divisions within the sequence must be defined by rather arbitrary criteria and are usually difficult to locate accurately in the field. In this study the rocks of areas A through D were divided into the following map units, from the stratigraphic (and locally structural) base upwards:

1) Layered ultramafic rocks.
2) Interlayered gabbroic and ultramafic rocks.
3) Homogeneous gabbroic rocks.
4) Sheeted diabase dikes.

The general characterisitics of each of these units are described in subsequent sections of this chapter. For the purpose of simplicity, all rock types referred to, unless otherwise mentioned, are original igneous compositions presumed to have existed prior to any metamorphism and alteration. A more detailed discussion of the igneous and metamorphic characteristics of the rocks of the study areas may be found in Chapter IV.

B. Layered Ultramafic Rocks

A sequence of layered ultramafic rocks comprises the stratigraphically lowest lithologic unit of the Betts Cove ophiolite. This unit is best displayed in area A, although it is exposed to some extent in all of the areas. The base of the layered ultramafic unit is everywhere truncated by steep faults.

Determination of the thickness of this unit is difficult for this reason, and is further complicated by uncertainties in the orientation of its upper contacts. The relatively straight nature of this contact in area A (as depicted on plate 2) suggests that it is rather steep and possibly subparallel with layering within the unit, however. A dip estimate of 60^{o} for the upper contact, based on the average orientation of adjacent layering, results in a value of 375 m for a minimum thickness perpendicular to the upper contact in area A. A somewhat thinner section is preserved in area B (average dip is approximately 50^{o}), while only the uppermost portion of the unit occur in C (dip is approximately 50^{o}) and D (dip is approximately 60^{o}).

This unit consists predominantly of interlayered coarse-grained ultramafic rocks. Gabbroic rocks comprise only a small portion of the unit and are generally concentrated near the top.

The lower portion of the unit is comprised predominantly of ultramafic rocks rich in olivine and orthopyroxene, and has an overall composition of approximately 40% harzburgite, 25% orthopyroxenite, 15% dunite, 10% websterite, and 10% lherzolite. These rocks generally contain only small amounts of interstitial clinopyroxene and are characterized by granular and interstitial textures. Upper portions of the unit are progressively more clinopyroxene-rich, and near the top significant amounts (5 to 30%) of plagioclase are sometimes present. The most abundant rock types seen near the top of the unit are plagioclase-bearing and plagioclase-free varieties of clinopyroxenite (20%), websterite (30%), lherzolite (40%), and dunite (10%), along with minor harzburgite, orthopyroxenite, and gabbroic rocks. Rocks from this upper zone generally show interstitial, poikilitic, and oikocrystic textures. The contact between the layered ultramafic unit and the overlying interlayered gabbro and ultramafic unit is gradational and was chosen to be the point at which the abundance of gabbroic rocks exceeds 10% on the scale of an average outcrop (100 m^2).

The rocks comprising the layered ultramafic unit are interlayered on a variety of scales ranging from several mm to 10 m or more in most places (Figures 4 and 5). Layering in lower portions of the unit is usually well-developed and averages 5 cm to 1 m in thickness. It tends to increase in thickness and become more vaguely defined toward the top of the unit, where layer thicknesses often exceed 10 m. In areas where layer thicknesses are great layering is often difficult to detect, as few layer contacts exist in any particular outcrop. Where it is well-developed, layering is commonly traceable over the entire width of individual outcrops, although in some cases layers pinch out over short distances, suggesting that in general they are not continuous on a large scale. Contacts between layers are usually sharp and are defined by compositional differences, grain-size differences, or both.

Grain-size grading within individual layers and gradational contacts between layers of similar lithology, but differing grain size, are seen in some areas, most commonly near the top of the unit. The best examples of these occur at a location southeast of Kitty Pond (Figure 6) first described by Upadhyay _et al._ (1971) and examined briefly during the course of this study. Both normal and reverse grading occurs in size-graded layers, although layers which fine towards the upper extrusive units of the ophiolite (normally graded layers) appear to be slightly more common.

Layers displaying compositional (mineralogical) grading are rare. Where it occurs, compositional grading is usually expressed by variations in the abundance of intercumulus clinopyroxene at various levels within individual layers. In some cases, this results from variations in the size of resorbed cumulus grains, resulting in layers which are graded in both grain size and composition.

Figure 4

Fine-scale igneous lamination within the layered ultramafic unit, area B. Grey layers are pyroxenite, brown layers are olivine-pyroxene rock. Hammer is approximately 25 cm high.

Figure 5

Large-scale layering in the ultramafic rocks of area A, north of Kitty Pond.

Figure 4

Fine-scale igneous lamination within the layered ultramafic unit, area B. Grey layers are pyroxenite, brown layers are olivine-pyroxene rock. Hammer is approximately 25 cm high.

Figure 5

Large-scale layering in the ultramafic rocks of area A, north of Kitty Pond.

Figure 6

Size-graded layer within the layered ultramafic unit south-east of Kitty Pond (plate 2, location 1). Lens cap in this and following photographs is approximately 6 cm in diameter.

A variety of small-scale igneous structures occur within the layered ultramafic unit, though most of them are not common. Trough and channel structures occur sporadically in well-layered portions of the unit (Figure 7). These range in width from 10 cm to 2 m and are usually shallow and poorly developed. Abrupt truncations of surrounding igneous layering occurs at the margins of the best examples, suggesting that they were produced by current scouring along the floor and/or walls of the magma chamber in which the layered ultramafic rocks were formed. It was not possible to determine current flow directions from these structures in most cases because good three-dimensional exposures of them are rare.

Rare examples of boudined layers were observed, with boudinage usually being restricted to one layer within a sequence of relatively intact layers. Individual boudins generally occur as tabular bodies aligned parallel with layering and are usually composed of rock more pyroxene-rich than that surrounding them. A weak to fairly intense foliation defined by flattened mineral grains commonly occurs in the layers immediately adjacent to boudined layers. The restriction of this boudinage and foliation to thin zones parallel with layering suggests that they were produced by localized, layer-parallel, brittle extension of one or more layers accompanied by ductile shearing in adjacent rocks. Such deformation may have resulted from the break-up and downslope sliding on the magma chamber floor and walls of brittle pyroxene-rich surface layers over less competent olivine-rich layers.

Linear and planar fabrics defined by aligned tabular mineral grains (usually pyroxene) are fairly common, and are well-developed in places (Figure 8). These generally do not appear to be of tectonic origin. They are commonly confined to one layer and exhibit no evidence of grain

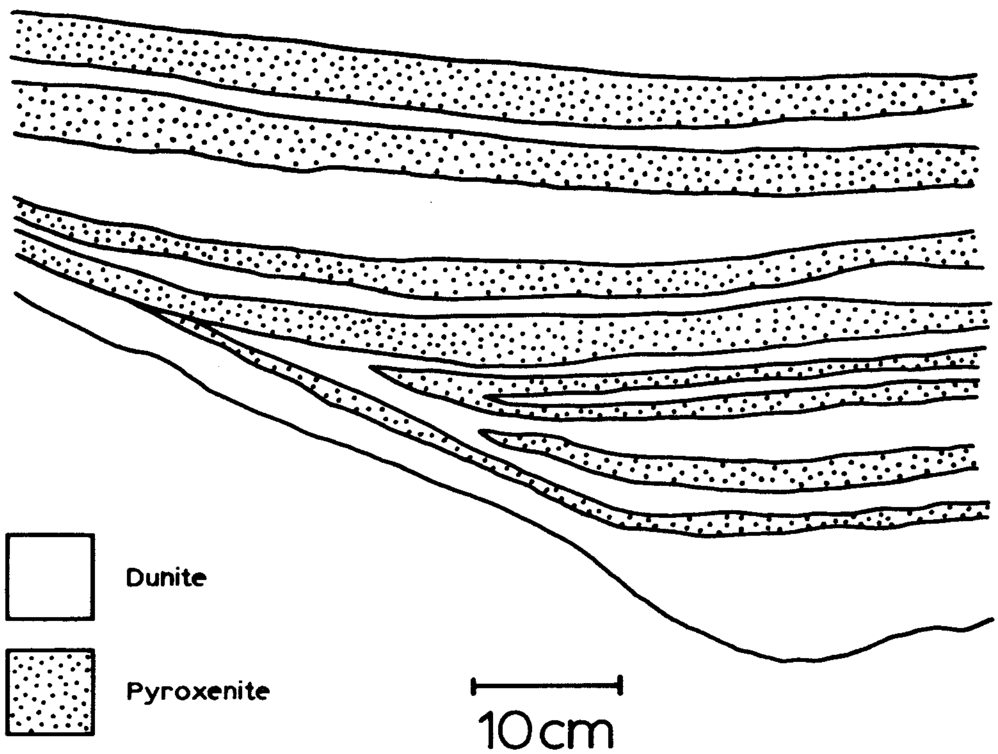


Figure 7

Channel structure, area A (plate 2, location 2).

Figure 8

Lineated harzburgite layer, area A. Light brown grains are orthopyroxene, darker reddish-brown grains are olivine.

deformation, the grains being perfectly tabular in nearly all cases. These fabrics are therefore interpreted as having been produced by magma chamber processes, such as the alignment of non-equidimensional grains on the magma chamber floor and walls by currents within the chamber. Similar structures of apparently similar origin occurring in the layered rocks of some other ophiolites and layered intrusions have been described by Jackson (1971) and Jackson, Green, and Moores (1975).

In general these lineations and foliations lie within the plane of the layering they occur in, but in some cases they occur at angles of up to 30^{o} to layering. In rare cases fabrics occurring within one layer at slight to moderate angles to its contacts are truncated at one or both contacts by adjacent layers, forming apparent cross-lamination within the layer.

Dikes of green, pegmatitic, plagioclase-bearing clinopyroxenite which cut layered rocks are fairly common in the layered ultramafic unit. These range in size from veinlets less than 1 cm thick to large dikes with thicknesses in excess of 2 m. Most are nearly perpendicular to layering in the rocks they cut. In nearly all cases they are not chilled against these layered rocks, though large clinopyroxene grains are often oriented perpendicular to the walls of the dikes. At several locations in areas A and B plagioclase-bearing clinopyroxenite dikes eminate both stratigraphically upwards and downwards from clinopyroxene-rich, largely plagioclase-free layers within the layered sequence (Figure 9). This relationship, and their lack of chilled margins, suggests that the dikes may have been derived from the filter-pressing or sweating of melt trapped in or flowing through these clinopyroxene-rich layers, or

Figure 9

Grey clinopyroxenite dikes cutting a peridotite layer (plate 2, location 3). Dikes "root" in pyroxenite layer at bottom of photograph.

from remobilized crystal mush injected from the layers, before they had crystallized completely. The similarity in composition between clinopyroxenite dikes and their source layers, and the high temperatures required to produce melts of this composition (greater than approximately 1300°C) tend to rule out the first mechanism, however. Dikes and small, irregular intrusive bodies of clinopyroxenite are most abundant in the uppermost portion of the layered ultramafic unit, where they locally comprise up to 50% of individual outcrops. They are usually quite thick here, often exceeding 2 m. Because this portion of the unit is comprised largely of clinopyroxene-rich rocks with thick, vaguely defined layers, many of these dikes are very difficult to see in outcrop.

Gabbroic rocks first appear approximately 75 m down from the top of the layered ultramafic unit, occurring as isolated and apparently rootless pegmatitic dikes and sills. These are 5 cm to greater than 1 m thick and can be traced for distances of up to 20 m in some places before pinching out or becoming lost in discontinuous outcrop. Gabbro becomes more abundant near the top of the unit, where it occurs as irregular, discontinuous layers, dikes, sills and irregular networks of thin anastomosing veins (Figure 10). Thin veins and dikes commonly branch off irregular gabbro layers. Intrusive gabbro veins grade compositionally into the surrounding rock in places, and in areas containing interlayered pyroxenite and peridotite they occur with greater abundance in the pyroxenite layers. This suggests that much of the intrusive gabbro was derived from basaltic melt or crystal mush trapped in and later injected from partially crystallized pyroxene-rich layers in a manner similar to that proposed for the clinopyroxenite dikes. Small tabular ultramafic xenoliths occur sparsely in some of the larger gabbroic intrusive bodies (Figure 11). In most cases these appear to be portions of

Figure 10

Anastomosing gabbro veins (white) cutting websterite (brown), area A.

Figure 11

Tabular websterite xenoliths (reddish-brown) in a small, gabbroic intrusive body (white), area B.

Figure 10
Anastomosing gabbro veins (white) cutting websterite (brown), area A.

Figure 11

Tabular websterite xenoliths (reddish-brown) in a small gabbroic intrusive body (white), area B.

thin ultramafic layers which comprise the wall rocks adjacent to the gabbroic bodies.

Widely separated podiform bodies of olivine- and orthopyroxene-rich ultramafic rocks completely surrounded by coarse-grained rocks with compositions ranging from clinopyroxenite to melagabbro are quite common near the top of the layered ultramafic unit. These have been described previously by Upadhyay et al. (1971) and Riccio (1972), both of whom suggested that they probably represent either true xenoliths or ultramafic layers extensively cut by intrusive clinopyroxenite. Most of them have a crude tabular shape, their long dimensions being parallel with layering in surrounding rocks (Figure 12). They generally range from 0.5 to 3 m in width and 1 to 5 m in length. Careful examination often reveals the presence of small-scale layering within these pods, which is again parallel with that in surrounding rocks. Although often widely separated (10 to 100 m), the pods usually occur in "trains" aligned parallel with the strike of layering, each "train" commonly displaying a distinctive composition and texture (W.S.F. Kidd, pers. comm., author's pers. obs.). Therefore, they probably represent remnants of original igneous layers extensively cut by intrusive clinopyroxenite rather than true xenoliths.

The best-displayed examples of intrusive clinopyroxenite and pods formed from the dissection of ultramafic layers than can be found in the ophiolite occur in the vicinity of Pittman Bight, approximately 5 km southwest of Betts Cove (plate 1). Peridotite exposed in coastal cliffs at this locality is extensively cut by pegmatitic clinopyroxenite bodies, which in places account for over 80% of the exposure. Individual tabular clinopyroxene grains in this clinopyroxenite exceed 10 cm in length in

Figure 12

Elongate podiform peridotite body (brown) surrounded by intrusive clinopyroxenite (grey), area A. Foliation and weak lamination within pod are parallel with regional layering.

some areas. In most places all traces of layering within the host peridotite is obscured by the irregular contact geometry of these clinopyroxenite bodies and by extensive alteration. The largest intrusive bodies are up to 10 m across, and commonly contain irregular pods of peridotite (Figure 13), some of which display poorly preserved igneous layering. Radial cracks in the clinopyroxenite surrounding these pods are common and are probably the result of the extensive serpentinization and accompanying volume increase of olivine within the pods.

True xenoliths were seen only at one locality, in area A (see plate 2). These occur as widely scattered, subrounded pods 25 cm to 1 m across (Figure 14). They are contained in a thick layer of coarse-grained orthopyroxene-rich harzburgite, and consist of oikocrystic olivine-rich harzburgite. Unlike most of the podiform bodies occurring in the upper portion of the layered ultramafic unit, these occur at random levels within their containing layer, and exhibit no evidence of having been produced by the dissection of a once continuous layer or layers. In addition, they contain large quantities of intercumulus orthopyroxene which surrounds and replaces cumulus olivine grains, a textural relationship which apparently does not occur in any other layered ultramafic rocks of the Betts Cove ophiolite. Since no possible parent material for these xenoliths exists within the layered ultramafic unit, it is probable that they were derived from lower levels within the ultramafic sequence. Some of the ultramafic rocks of area E exhibit similar textures and may represent a sampling of these levels (see Section F).

Rodingitized margins are characteristic of many of the gabbroic bodies within the layered ultramafic unit. These occur as 1 to 10 cm

Figure 13

Peridotite pod within intrusive pegmatitic clinopyroxenite, Pittman Bight. Note coarse grain size of clinopyroxenite and radial fractures surrounding pod.

Figure 14

Harzburgite xenolith (light brown) within a thick harzburgite layer (dark brown), area A (plate 2, location 4).

thick, extremely fine-grained, chalky white zones which grade inward into coarser-grained, less altered gabbro. Rodingitization appears to be most extensive in areas where the wall rocks are highly altered. Where gabbroic rocks cut layered pyroxenites and peridotites, rodingitization is usually more intense adjacent to the peridotite layers, presumably due to their more extensive serpentinization.

Rare, highly altered, fine-grained mafic dikes (referred to as early dikes in Chapter 4) cut the uppermost 150 m of the layered ultramafic unit in places. These dikes decrease in abundance downwards and are generally absent from lower exposures of the unit. They comprise a negligible portion of the unit as a whole. Individual dikes cannot be traced for more than 25 m in most cases, and no examples of dike terminations were observed.

Fine-grained dikes generally range from 10 cm to 1 m in thickness. They usually shown well-developed chill margins against surrounding coarse-grained rocks. Most dikes are picritic and contain 10 to 35% altered phenocrysts or xenocrysts (usually olivine and orthopyroxene) which are commonly concentrated in their centers, presumably as a result of flow differentiation. These usually weather in relative to the finer-grained matrix, giving dike weathered surfaces a pitted appearance (Figure 15).

In areas containing both fine-grained dikes and coarser-grained intrusive rocks, the fine-grained dikes are always seen to cross-cut and post-date the coarser rocks, and are usually chilled against them (Figure 16).

The fine-grained dikes of the layered ultramafic unit are generally sub-parallel with those of the overlying sheeted diabase dike unit. In

Figure 15

Fine-grained picritic diabase dike within the layered ultramafic unit, area A. Pitted appearance is due to the extensive weathering of numerous phenocrysts or xenocrysts.

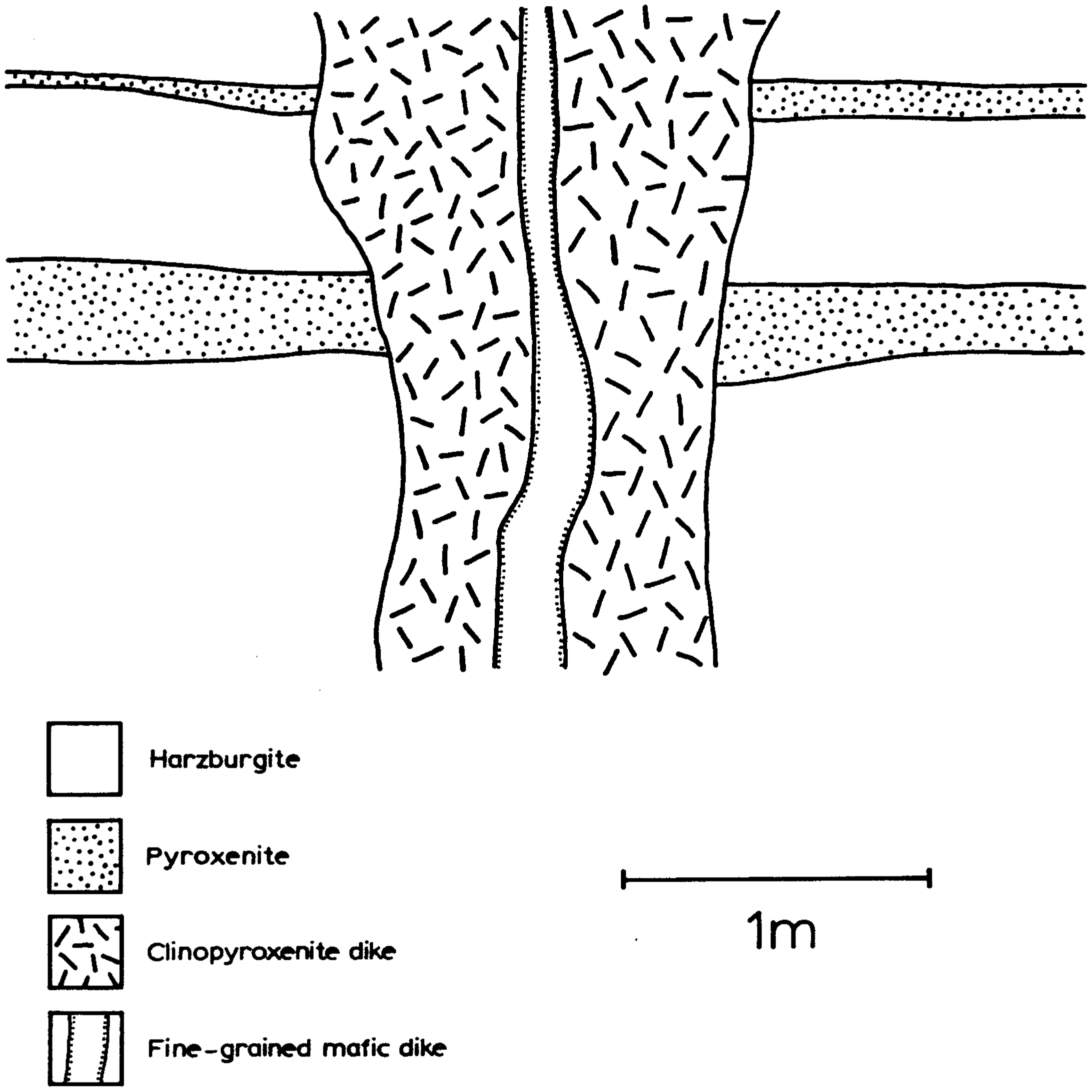


Figure 16

Fine-grained mafic dike intrusive into and chilled against intrusive clinopyroxenite dike, area C (plate 2, location 5).

areas A, C, and C they increase gradually in abundance as the sheeted dike unit is approached, with no evidence of major intervening structural discontinuities or cross-cutting relationships suggestive of the presence of multiple dike sets. For these reasons, the fine-grained dikes of the layered ultramafic unit (and the overlying gabbroic units) are interpreted to have been produced by the same phase of dike injection that produced the dikes of the sheeted dike unit.

C. Interlayered Gabbroic and Ultramafic Rocks

Above the layered ultramafic rocks in map areas A through D is a thin unit composed predominantly of interlayered ultramafic and gabbroic rocks. Although somewhat different in composition, this unit shares many common characteristics with the layered ultramafic unit. As is true of the layered ultramafic unit, the thickness of this unit is difficult to determine, due largely to uncertainties in the locations and orientations of its bounding contacts. Map relationships suggest, however, that the contact orientations are generally sub-parallel with adjacent igneous layering. Assuming that contact dips are approximately equal to the dips of adjacent layering (as was done in the case of the layered ultramafic unit), the unit has a thickness of 180 m in area A (a maximum possible thickness of 230 m is obtained if vertical bounding contacts are assumed). Similar thicknesses occur in areas B and D, although both bounding contacts are not exposed in these areas. The actual maximum thickness of the unit may therefore be greater than this value. A thin sequence occurs in area C, where only 65 m (assuming 60^{o} contacts) of this unit exists with both bounding contacts exposed.

The nature of the upper contact of the interlayered unit is quite variable across the ophiolite. In area D the interlayered rocks pass upwards into homogeneous gabbro of the massive gabbro unit across a contact which is relatively unobscured by cross-cutting diabase dikes. This contact is very gradational and difficult to locate precisely in the field in most places. In general it was defined as the point at which readily discernable and measureable layering disappears, on an outcrop scale, going upwards through the plutonic section. A similar sequence is seen in area C, although the upper portion of the interlayered unit and all of the overlying massive gabbro unit contain a large proportion (10 to 95%) of diabase dikes. Despite this, the contact between the two units is quite apparent and is defined in the same manner as in area D. In area A, diabase dikes are very abundant in the upper third of the interlayered unit, and increase in abundance rapidly upwards. Approximately 180 m above the lower contact of the unit the dikes become sheeted and comprise 95 to 100% of the exposure. Coarse-grained screens between the dikes are generally too sparse and small to classify them as belonging to either the interlayered or isotropic gabbro units, though plutonic rocks immediately below this stratigraphic level are clearly well-layered. The top of the interlayered unit in this area is therefore defined to be the point at which the proportion of diabase dikes exceeds 95%, estimated on the scale of a typical 100 m^2 outcrop.

Because of the variations existing in the abundance of diabase dikes cutting the interlayered unit in different parts of the complex, the unit was subdivided on plate 2 into dike-poor and dike-rich members where possible. The proportion of dikes distinguishing the two members was chosen to be 10%. Since few quantitative measurements of the dike contents of individual outcrops were carried out, the location of the contact between the dike-poor and dike-rich zones is probably somewhat imprecise in many places.

The plutonic rocks in the lower portion of the interlayered unit consist predominantly of interlayered, coarse-grained plagioclase-bearing websterite, clinopyroxenite, and gabbronorite, with lesser gabbro. Both melanocratic and leucocratic gabbroic rocks occur in approximately equal proportions. Olivine-bearing gabbroic and ultramafic rocks are rare in most places, with the exception of area B, where they occur throughout the lower portion of the unit in small quantities. In other areas olivine-bearing rocks disappear rapidly above the upper contact of the layered ultramafic unit. The overall composition of the lower half of the unit, averaged over all of the map areas, is approximately 50% gabbro, 40% plagioclase-bearing websterite and clinopyroxenite, and 10% olivine-bearing gabbroic and ultramafic rocks.

This mafic/ultramafic sequence becomes progressively enriched in clinopyroxene relative to orthopyroxene near the top of the interlayered unit, which consists mostly of gabbro and plagioclase-bearing clinopyroxenite, with minor plagioclase-bearing websterite. Olivine-bearing rocks are absent or very rare at this level in most parts of the complex, occurring only as isolated, lensoid layers. On an average, the upper half of the interlayered unit consists of 70% gabbro and 30% plagioclase-bearing clinopyroxenite.

Grain-size variation in plutonic rocks of the interlayered unit is somewhat greater than that seen in the layered ultramafic unit. Though most of the interlayered rocks are coarse-grained, a significant proportion (10 to 20%) have grain sizes which fall outside of the range normally seen in the ultramafic sequence. These are approximately equally divided between very coarse-grained (pegmatitic) and fine-grained (microcrystalline) varieties.

Igneous layering in the interlayered unit is generally similar to that seen in the layered ultramafic unit. Layer thicknesses range from several mm to over 5 m, with most of the unit being composed of 10 cm to 1 m thick layers. Layer thicknesses appear fairly consistent throughout the unit, although the thickest layers are generally concentrated near the bottom. Discontinuous and lens-shaped layers are somewhat more common in this unit than in the ultramafic sequence. Thin layers (less than 20 cm thick) tend to be less continuous than thicker ones and may be seen to pinch out at both ends in places, producing lensoid bands with lengths of 50 cm to several m or more on outcrop faces (Figure 17). No evidence of boudinage, tectonic disruption, or sedimentary scouring exist within or adjacent to these layers in most places, and they are often bounded by the same rock type at both upper and lower contacts. They probably originated as the result of small-scale variations in crystallization or deposition within the ophiolite magma chamber.

Layer contacts range from sharp to diffuse. In most places they are somewhat gradational over distances of several mm to several cm and are characterized by changes in both composition and grain-size, although grain-size differences between adjacent layers are usually small. Well-defined mineralogical and grain-size grading within individual layers is rare, but diffuse, irregularly shaped patches exhibiting slight variations in both mineralogy and grain size are common.

Mesoscopic igneous features such as channel structures are almost completely absent from the interlayered unit. Apart from layering, the only structures commonly seen in outcrop are linear and planar fabrics defined by the preferred orientation of mineral grains. They are generally similar to those seen in the layered ultramafic unit, with little or no

Figure 17

Tabular and lensoid layering within the interlayered unit, area D. White layers are leucogabbro, reddish-brown layers are micromelagabbronorite.

apparent deformation of individual grains. These fabrics lie within the plane of igneous layering and, like those of the layered ultramafic unit, are inferred to have been produced by the alignment of inequant grains into parallelism with magma flow directions.

Several isolated examples of foliations defined by moderate to intense flattening of originally tabular? plagioclase and pyroxene grains occur in area D. These are quite variable in orientation over short distances (less than 1 m) and commonly occur at high angles to igneous layering. In no case are they traceable for more than approximately 3 m. The variable orientation and limited extent of these foliations suggest that they were probably produced by the local instability and slumping of partially crystallized mush along the margins of the magma chamber. Widespread and consistently oriented tectonic fabrics like those occurring in the layered, "cumulate" plutonic rocks of the nearby Bay of Islands ophiolite complex (Casey, 1980; Casey, et al., 1981) and other ophiolites (i.e. Mings Bight, Kidd et al., 1978) are not seen at Betts Cove.

Coarse-grained to pegmatitic dikes, sills, and small irregular intrusive bodies are common in the interlayered sequence. These generally range in composition from clinopyroxenite to leucogabbro. They occur with greatest abundance near the bottom of the unit, where they locally comprise up to 40% of the exposure. This value decreases sharply upwards, with coarse-grained intrusives generally accounting for less than 5% of the exposure in the upper half of the unit. Intrusive gabbro and leucogabbro occur throughout the interlayered unit, while clinopyroxenite is usually found only near the bottom.

These intrusive rocks are generally similar in composition and mode of occurrence to coarse-grained intrusives occurring in the upper portion of the layered ultramafic unit. They occur most commonly as tabular dikes 10 cm to 2 m or more in thickness which are usually oriented subperpendicular to igneous layering. Thin anastomosing veins, small irregular intrusive bodies, and rare sills also occur. No evidence of chilling exists along their margins, but a strong alignment of tabular grains perpendicular to the walls of these intrusive bodies is common. This is most evident in pegmatitic leucogabbro dikes. In some places, dikes and veins can be shown to root in layers of roughly similar composition, a relationship also observed in the layered ultramafic unit (see Figure 9). In a few of these examples, the intrusive rocks are coarser-grained and slightly more leucocratic than the layers from which they eminate, possibly the result of having been derived from interstitial melt which was rich in normative plagioclase relative to the bulk composition of the partially crystallized layers it was derived from. At a few localities cross-cutting dikes with slightly to moderately differing compositions were observed in one outcrop. In most cases it can be demonstrated that the most leucocratic dikes are the latest, although in rare cases this relationship is contradicted. In general, the coarse-grained intrusive rocks of the interlayered unit appear to be closely related to those occurring further down in the ultramafic unit, and have probably been formed by similar processes.

Rare pods of ultramafic rock surrounded by clinopyroxenite or melagabbro occur immediately above the lower contact of the interlayered unit in a few places, the best examples being found in area B. These appear to be similar in occurrence and origin to those of the layered ultramafic unit.

Fine-grained mafic dikes (mostly altered diabase?) which occur within the interlayered unit have been mentioned previously. These dikes are inferred to be related to those of the sheeted diabase dike unit and are generally similar to those dikes cutting layered ultramafic rocks described in the preceding section, with several differences. Many of the dikes cutting the interlayered unit are somewhat less altered, and in some of them igneous mineralogy and textures are preserved well enough to allow them to be classified as altered diabases. In addition, these dikes are commonly more abundant here than in the layered ultramafic unit, and are locally sheeted near the top of the unit. Dikes within these sheeted zones display complex intrusive (chilling) relationships similar to those seen in the overlying sheeted dike unit.

Examples of igneous relationships between coarse- and fine-grained intrusive rocks are abundant in the interlayered unit (Figure 18). As in the layered ultramafic unit, fine-grained dikes can always be shown to post-date coarse-grained intrusive rocks where cross-cutting relationships between them occur.

D. Homogeneous Gabbro

A rather monotonous unit of poorly layered to homogeneous gabbroic rocks overlies the interlayered sequence in areas C and D, and occurs within a fault-bounded block in area E. Structural complexities prevent any reasonably accurate determination of the thickness of this unit in areas D and E, but an intact section in area C yields an approximate thickness of 195 m. This figure was obtained by assuming that the bounding contacts of the homogeneous gabbro unit are parallel with the lower contact of the underlying interlayered unit (see Section 4C). This assumption was necessary because three-dimensional exposures are com-

Figure 18

Fine-grained, altered diabase dike (pink/orange) cutting clinopyroxenite (greenish-grey) and intrusive leucogabbro vein (white), area A. Note pale, chalky chilled margin on dike.

pletely lacking along the unit contacts in area C, and little evidence which sheds any light on the contact orientations exists within the unit.

The homogeneous gabbro unit passes upwards into the sheeted dike unit by a gradual increase in the abundance of diabase dikes within the gabbro. The contact between the two units was chosen to be the point at which the average abundance of dikes exceeds 95%, following the scheme used to define the interlayered unit/sheeted dike unit contact in the preceding section.

The compositional range of the rocks comprising the bulk of the homogeneous gabbro unit is quite small. Approximately 90% of the unit consists of medium to coarse-grained metabasites, along with gabbro and leucogabbro from which the metabasites were apparently derived. Medium to coarse-grained clinopyroxenite and websterite account for the remaining 10%. These ultramafic rock types generally occur very close to the lower contact and are rare throughout the central portion of the unit. They also occur locally as isolated screens between diabase dikes near the top of the unit.

Well-developed igneous layering is rare in the homogeneous gabbro unit. It occurs almost exclusively within the lowermost 50 m and disappears rapidly upwards. The layering in this part of the unit is very locally developed and is only seen in about 5% of the exposure. In most cases it cannot be traced into adjacent outcrops, and in some places it can be seen to disappear along strike within one outcrop. This layering is defined in most places by very slight differences in both composition and grain size. Individual layers are generally quite thin, with average thicknesses ranging from 5 to 50 cm. Where it is possible to measure this layering, it is generally subparallel with layering in the underlying units.

In the remainder of this lower zone and in the overlying portions of the unit well-developed igneous layering is absent. Outcrops here tend to be fairly homogeneous with respect to composition and grain size. Careful examination often reveals subtle variations in these properties on a small scale, however (Figure 19). Small, highly irregular patches of coarse-grained to pegmatitic gabbro are common within extensive areas of medium-grained gabbro. These patches range from 2 cm to 1 m across, and usually have very diffuse margins which grade over distances of 2 to 20 cm into the surrounding rock. In many cases the patches are slightly more leucocratic than the gabbro enclosing them. Thin, highly irregular and discontinuous layers defined by slight compositional and/or grain-size variations are also common. These are usually less than 5 cm thick and have sharp margins. They are rarely traceable for more than 1 m, and have orientations which are usually very inconsistent within individual outcrops, often varying by up to 90°. The layers themselves are usually curving and irregular in shape over short distances. They appear to terminate most commonly by pinching out or grading laterally into the surrounding rocks. The irregular and discontinuous nature of this layering suggests that it probably formed by localized variations in in situ crystallization in portions of the ophiolite magma chamber not dominated by large-scale crystal transport and deposition.

In addition to layering, a number of other features common to the underlying layered units do not appear to occur in the homogeneous gabbro unit. These include igneous lineations and foliations, coarse-grained intrusive rocks, ultramafic and gabbroic pods, and xenoliths.

Metabasites containing 10% or greater quartz occur in small quantities throughout the homogeneous gabbro unit in all areas. They are most

Figure 19

Small-scale igneous structures within the homogeneous gabbro unit, area C. Note patchy grain size variation and thin, irregular layer at center-right.

abundant in area D, where they are concentrated in an area approximately 250 m across. In most places they are found as small, irregular pod-like bodies 1 to 20 m across. The rocks comprising these pods are very similar in appearance to the surrounding rocks except that they appear in outcrop to be somewhat more altered. The weathered surfaces of these rocks are usually chalky white in color, and abundant dark brown to black hornblende is usually evident. Most samples contain enough coarse-grained quartz to allow them to be easily identified in the field. The margins of these pod-like bodies are very diffuse, the quartz-bearing rocks generally grading into the surrounding gabbroic rocks by a gradual decrease in quartz content and apparent extent of alteration over distances of several centimeters to tens of meters. Petrographic evidence (summarized in Chaper 4) suggests that the quartz in these rocks was formed as the result of low-grade (possibly ocean-floor?) metamorphism subsequent to their crystallization. In most cases they are too extensively altered to allow a determination of their igneous protoliths to be made, but partially preserved original igneous textures and mineral assemblages in a few samples show that the original compositions and textures of these metabasites were probably similar to the less-altered rocks of the homogeneous gabbro unit.

Altered diabase dikes cutting the homogeneous gabbro unit are generally similar to those occurring in the interlayered unit; for descriptions of these dikes the reader is referred to the previous section.

E. Sheeted Diabase Dikes

A unit consisting almost entirely of diabase dikes gradationally overlies the plutonic rocks of the Betts Cove ophiolite. Spectacular exposures of this unit occur along the cliffs of Betts Cove and in the valley between Betts Cove and Kitty Pond. Since no complete sections of the sheeted dike unit exist in the portions of the complex mapped in detail during this study it was not possible to accurately determine its total thickness. A 260 m thick section with a faulted upper contact occurs in area A, however. Upadhyay (1973) and Riccio (1972) report maximum thicknesses of 1 to 1.6 km from other areas within the complex. In most places dikes of the sheeted dike unit are approximately perpendicular to igneous layering in underlying units of the complex, especially in lower portions of the dike unit. In some areas (most notably area D), however, dike orientations have been strongly affected by folding believed to post-date the formation of the ophiolite (see Chapter 5).

The sheeted dike unit consists, on an average of more than 95% subparallel, altered diabase dikes (Figure 20), with minor but ubiquitous coarse-grained rocks comprising the remainder. The presence of these sheeted dikes within the Betts Cove ophiolite was first recognized by Baragar (1954), who suggested that they had been produced by "persistent, slow-acting" extension. Similar sequences of sheeted dikes occur in numerous other ophiolite complexes and are generally thought to be formed as the result of 100% extension occurring at an oceanic spreading axis (Moores and Vine, 1971). Brock (1974) has suggested that the Betts Cove dikes are not a produce of sea-floor spreading because the underlying plutonic portion of the complex shows no evidence of having undergone large amounts of extension. Subsequent discussions by Church and Riccio (1974) and Strong and Malpas (1975) have shown that such extension is not necessary for the production of the dike unit by 100% extension,

Figure 20

A typical exposure of the sheeted dike unit, area D.

however, and would not be expected to occur during ophiolite generation.

Individual dikes of the sheeted dike unit range from several cm to over 3 m in thickness, although most are approximately 50 cm thick. Many display well-developed chilled margins which appear as fine-grained, chalky weathering, 1 to 10 cm thick zones along dike margins. Dikes may contain zero, one, or two chilled margins, a criteria which can be used to determine their ages relative to neighboring dikes. No attempt was made during the course of field work to do a statistical study of one-way chilling directions within the dikes, although a study of this type has been done on several sections of Betts Cove dikes by Kidd (1977). He concluded that most of the dikes had been intruded in a narrow zone less than 50 m wide, but was unable to detect a preferential one-way chilling direction within the sections.

In some areas dikes can be traced downwards into the underlying plutonic rocks. They can usually be seen to terminate in the plutonic rocks by pinching out, but in a few places, the bases of individual dikes are marked by intrusive contacts where coarse-grained plutonic rocks (usually gabbro) have intruded the dikes. This relationship is most evident in areas C and D, where relatively thick sequences of gabbroic rocks underlie the sheeted dike unit.

Coarse-grained rocks comprise up to 5% of the sheeted dike unit, generally occurring as screens between dikes. These are commonly 10 cm to more than 2 m in thickness. In most cases they can be seen to pinch out at both ends, and are traceable for 1 to 10 m. Dikes adjacent to these screens are usually chilled against them, although in rare examples one or both margins of a screen may show evidence of intrusion into an adjacent, pre-existing dike. This suggests that the screens probably represent intrusions roughly contemporaneous with the dikes, rather than older, cold "country rock" into which the dikes were intruded. Most of the screens occurring within the sheeted dike unit may be classified as gabbros or leucogabbros, although screens of ultramafic composition (usually plagioclase-bearing clinopyroxenite or websterite) occur in some places, even in areas where the dike unit overlies thick gabbroic sequences. Corase-grained screens are most common near the bottom of the sheeted dike unit, but in most areas they are present (on an outcrop scale) throughout the unit.

Rare examples of brecciated dikes occur in some areas (Figure 21). These usually show rusty weathering colors and are highly altered. They contain numerous 1 to 10 cm, angular to sub-rounded clasts of altered diabase in a rusty, fine-grained matrix. In some cases brecciated dikes occur as isolated examples within exposures of predominantly intact dikes, but in general they occur together in zones consisting of several dikes or more having total widths of up to 2 m. These zones probably served as hydrothermal conduits during the formation of the ophiolite. Similar brecciated dikes from the sheeted dike complex of the Bay of Islands ophiolite complex have been described by Williams and Malpas (1972).

F. Origin of the Ultramafic Rocks of Area E

Portions of area E are underlain by serpentinized ultramafic rocks (referred to as "homogeneous ultramafic rocks" on plate 2). Although these rocks are quite altered relative to most of the other rocks of the ophiolite complex, igneous features are partially preserved in some of them. Because they exhibit a number of important differences relative to the rocks of the layered ultramafic unit which occur in other areas, it was decided to classify them separately.

Figure 21

Brecciated dike within the sheeted dike unit, area D.

These ultramafic rocks have a very limited range of compositions and in most cases may be classified as orthopyroxene-poor harzburgites or dunites. They occur in outcrop as coarse-grained, homogeneous, pale orange weathering rocks largely devoid of any recognizable mesoscopic igneous structures (layering, grading, etc.). Orthopyroxene grains stand out in relief on weathered surfaces as blocky grains showing little or no evidence of any tectonic deformation, although igneous textures are also generally not recognizable. In some places the ultramafic rocks are cut by rare, highly altered, fine-grained mafic dikes similar to those occurring within the layered ultramafic unit.

In most ultramafic samples collected from this area igneous textures are wholly destroyed. A few, however, show partially preserved textures in thin section, even though they are extensively altered. In these samples orthopyroxene (bastite) poikilitically surrounds rounded, serpentinized olivine grains. This textural relationship does not occur in any ultramafic rocks from areas A through D, with the exception of a harzburgite xenolith from area A. In addition, these rocks contain chromite grains which are larger, more irregular in shape, and more translucent than any occurring in rocks of the layered ultramafic unit.

The origin of the ultramafic rocks of area E is unclear, but they may represent ultramafic tectonites similar to those occurring at the base of many intact ophiolite complexes (Church, 1972; Conference Participants, 1972; Irvine and Findlay, 1972). The harzburgitic composition, homogeneous nature, and lack of igneous features in the area E ultramafics all lend support to this hypothesis. On the other hand, the apparent lack of deformational features does not, although the deformation within ophiolitic ultramafic tectonites is variable from place to place and is not always evident on a mesoscopic scale (Casey, 1980; pers. obs.). In addition, chromite grains similar to those occurring in the Betts Cove samples are common within the basal harzburgite tectonites of the Mings Bight ophiolite (W.S.F. Kidd, pers. comm.) and the Bay of Islands ophiolite (J. Casey, pers. comm.).

The Snooks Arm Group, with the Betts Cove ophiolite at its base, forms the west limb of an overturned northeast-plunging syncline (Upadhyay, 1973), the east limb of which may be represented by the Western Arm Group of Green Bay (Neale and Kennedy, 1967; Marten, 1971). In a general sense, stratigraphic depth increases westward within the Snooks Arm syncline (see plate 1). Therefore, the ultramafic rocks of area E occupy a low 'stratigraphic' position within the ophiolite, one in which ultramafic tectonites would be expected to occupy if they were present. Available evidence is too meager to allow more than speculation as to the origin of these rocks, although a detailed study of all of the ultramafic rocks along the west side of the Betts Cove ophiolite might shed more light on this problem.

CHAPTER IV

LITHOLOGIC DESCRIPTIONS AND PETROGRAPHY

A. Introduction

A wide variety of rock types occur in the portions of the Betts Cove ophiolite investigated during this study. These fall into five general categories:

1) Ultramafic rocks.
2) Gabbros and related mafic plutonic rocks.
3) Diabase dikes.
4) Serpentinites, rodingites, breccias, and other rocks related to faults and zones of high strain or alteration.
5) Non-ophiolitic igneous and sedimentary rocks adjacent to the ophiolite.

The rocks of these categories are described individually in this chapter. For descriptive purposes these categories have been defined predominantly by composition rather than association within the ophiolite sequence. A general correspondence exists between some of these groups and the map units described in Chapter 3, although most of the map units contain several of these rock types in varying proportions.

Following the precedent adopted in the preceding chapter, all rock types mentioned in this chapter are presumed to represent original igneous compositions existing prior to metamorphism and alteration, unless otherwise stated.

Several different classification schemes have been used to classify the rocks of the study areas. Coarse-grained igneous rocks have been classified according to a system modified slightly after Streckeisen

(1973). Fine-grained igneous rock classifications are based on Hatch, Well, and Wells (1972). An average grain size of 0.5 mm was used to classify rocks into one of these two groups in an effort to differentiate between plutonic and hypabyssal rock types. Most hypabyssal rocks have average grain sizes (excluding phenocrysts) of less than 0.5 mm. The only exceptions to this are pegmatitic gabbro and pyroxenite dikes, which have been classified in the same manner as other coarse-grained rocks. All plutonic rocks have average grain sizes larger than 0.5 mm, with the exception of minor occurrences of fine-grained rocks as layers in predominantly coarse-grained layered sequences. In an effort to avoid certain genetic connotations commonly placed on rocks given fine-grained names (i.e. their presumed occurrence as hypabyssal intrusions or volcanics) these rocks have been given the same names as their coarse-grained equivalents preceded by the term 'micro'.

Igneous textures as seen in thin section are generally as described by Williams, Turner, and Gilbert (1954). Some rocks (most notably some of the layered plutonic rocks) show mesoscopic evidence for being of cumulate origin; terms describing certain textural characteristics of these have been taken from Jackson (1961) and Wager, Brown, and Wadsworth (1960). Metamorphic textural terms are from Spry (1969).

Other terms and definitions used in rock descriptions are defined in the text where necessary.

B. Ultramafic Rocks

Ultramafic rocks comprise most of the layered ultramafic unit and portions of the overlying gabbroic sequence. These ultramafic rocks are generally coarse-grained and consist of varying amounts of olivine, orthopyroxene, clinopyroxene, plagioclase, and chromite, all more or less altered. Most of these rocks may be classified as harzburgite, lherzolite, websterite, or orthopyroxenite. Present but less abundant are dunite, clinopyroxenite, and wehrlite (Figure 22). Plagioclase-bearing (plagioclase <10%) and plagioclase-free varieties of all of these types seem to occur in approximately equal proportions, although problems in identifying plagioclase in the field (discussed below) make this estimate somewhat speculative.

The distribution of these rocks is readily ascertained in the field by their distinctive reddish to brownish weathering colors. These vary, depending primarily upon the relative abundances of olivine and pyroxene present. Olivine-rich rocks appear orange, tan, or light brown, while orthopyroxene and clinopyroxene-rich rocks tend to weather to reddish-brown and green or grey colors, respectively. In more highly serpentinized rocks grey to bluish-grey weathering is generally seen. Fresh surfaces are generally dark-green to black in olivine-rich samples, with pyroxene-rich samples showing lighter green to grey colors.

Individual minerals in these rocks are usually partially to completely altered, but because textures are generally well preserved they can be identified in most cases by the weathering characteristics of their alteration products. Altered olivine appears dull yellow to orange and tends to be more susceptible to weathering than any other mineral present, commonly occurring as depressed or pitted areas on weathered surfaces. Pyroxenes are more resistant to weathering than olivine and weather in relief. When both are present clinopyroxene is usually more resistant than orthopyroxene. Clinopyroxene may occur in any stage of alteration from completely fresh to completely altered, usually to a tremolite-actinolite amphibole. In nearly all cases it appears bright

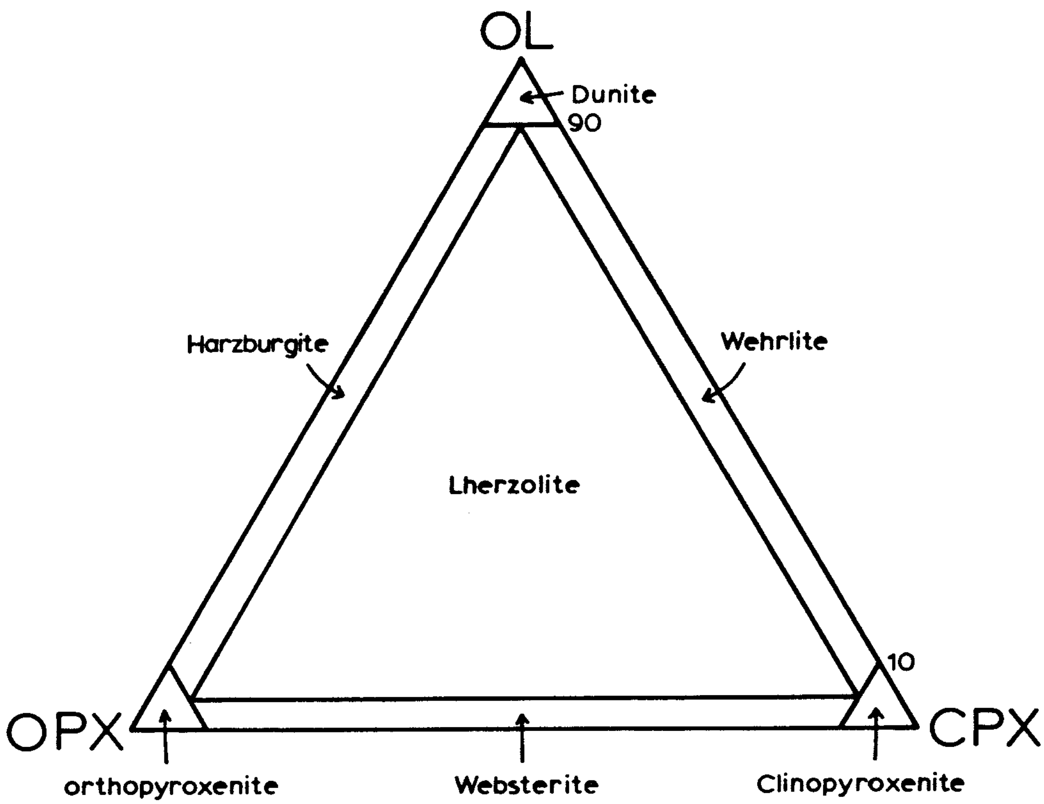


Figure 22

Classification scheme used for Betts Cove ultramafic rocks.

green on weathered surfaces, regardless of the extent of alteration. Altered orthopyroxene is commonly dull reddish-brown, although in some cases the alteration of orthopyroxene to tremolite produce green weathering colors, making it difficult to distinguish from clinopyroxene. Chromite appears as very small scattered black grains commonly displaying a metallic luster, presumably as a result of rimming by magnetite.

Textural and petrographic evidence suggests that many of the ultramafic rocks examined were originally plagioclase-bearing. In most examples all original igneous plagioclase has been altered to very fine-grained aggregates of chlorite, which usually weather reddish or reddish-brown. Much of this altered plagioclase is impossible to distinguish in the field from other minerals present, most notably orthopyroxene. This has presumably resulted in an unavoidable excess of orthopyroxene in the modes of many rocks classified in the field. Problems with the field identification of plagioclase are most severe in rocks containing appreciable amounts of olivine, since plagioclase alters most extensively in these rocks. Plagioclase occurring in orthopyroxenites is also extensively altered in most cases. Some less-altered clinopyroxenites and websterites contain slightly to moderately altered plagioclase which is recognizable in the field.

Many of the layered ultramafic rocks show interesting mesoscopic textural relationships. The terms granular, interstitial, poikilitic, and oikocrystic were used in the field to describe the variety of textural types seen. Granular textures are seen in rocks containing rounded, equant grains of presumed cumulus origin in a tightly packed configuration with no apparent interstitial material, this being most characteristic of dunites, orthopyroxenites, and harzburgite. In other cases scattered grains of an interstitial mineral (usually clinopyroxene) occupy spaces between rounded cumulus grains. This was described in the field as interstitial texture and commonly occurs in websterites and lherzolites. An increase in the abundance of interstitial minerals results in poikilitic texture, in which interstitial grains form a continuous "net" around cumulus grains. In a few instances large, isolated, "spongy" oikocrysts (see Jackson, 1961) of clinopyroxene from several mm to over 3 cm across surround and include rounded cumulus grains, usually olivine and orthopyroxene. Rocks containing abundant examples of these oikocrysts were termed oikocrystic.

The extensively altered nature of most of the ultramafic rocks is very apparent when examined in thin section. However, the preservation of original igneous textures and the generally consistent and distinctive nature of the alteration products of original igneous minerals aid in their identification when completely altered (Figures 23 and 24).

Olivine as seen in thin section occurs most commonly as rounded, anhedral grains 0.5 to 8 mm across and is completely serpentinized in all of the rocks examined (Figure 23). Upadhyay (1973) reports finding a few samples containing relic olivine, but a search through the least-altered samples collected in this study yielded only low relief, weakly birefringent serpentine with no unaltered olivine relects.

Serpentinized olivine is recognized primarily by the presence of a distinctive anastomosing arrangement of colorless to pale green cross-fiber serpentine veins (presumably chrysotile) which constitute up to 70% of altered grains. These veins commonly contain thin seams of fine-grained magnetite in their centers. In rare cases veins consist almost entirely of magnetite with only minor amounts of cross-fiber chrysotile

Figure 23

Photomicrograph of lherzolite from the layered ultramafic sequence. Small clinopyroxene oikocryst at center of field (at extinction) encloses partially resorbed, steatized, cumulus orthopyroxene (yellow) and serpentinized cumulus olivine (colorless) (crossed polars, short dimension of photograph equals 7 mm).

Figure 24

Photomicrograph of websterite from the layered ultramafic sequence. Marginally uralitized intercumulus clinopyroxene (yellow) poikilitically encloses rounded, completely steatized, cumulus orthopyroxene (crossed polars, short dimension of photograph equals 7 mm).

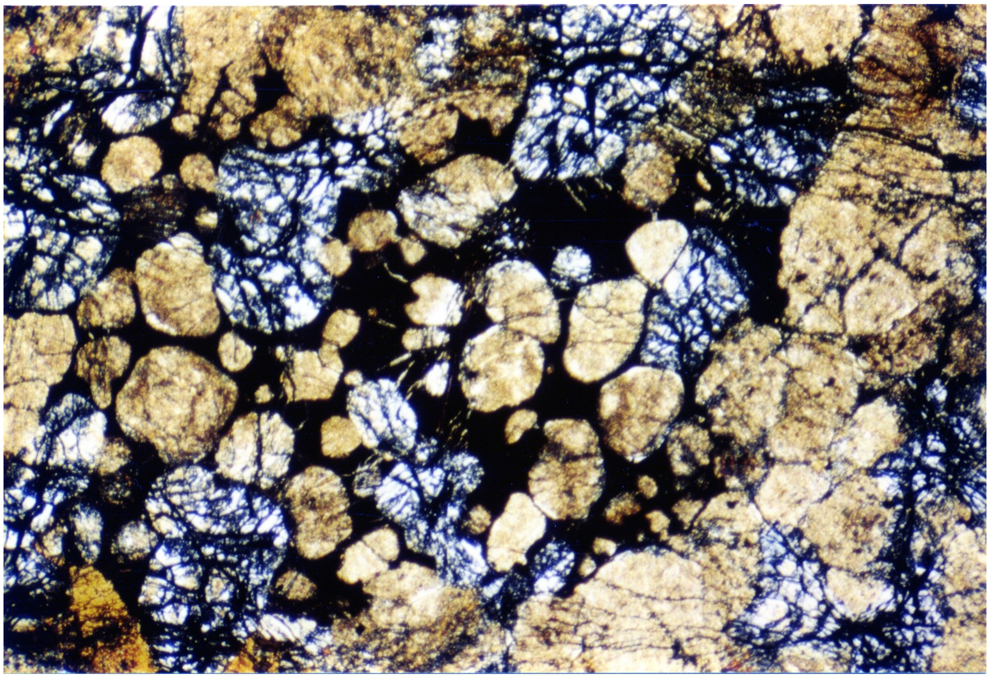


Figure 23
Photomicrograph of lherzolite from the layered ultramafic sequence. Small clinopyroxene oikocryst at center of field (at extinction) encloses partially resorbed, steatized, cumulus orthopyroxene (yellow) and serpentinized cumulus olivine (colorless). (crossed polars, short dimension of photograph equals 7 mm).

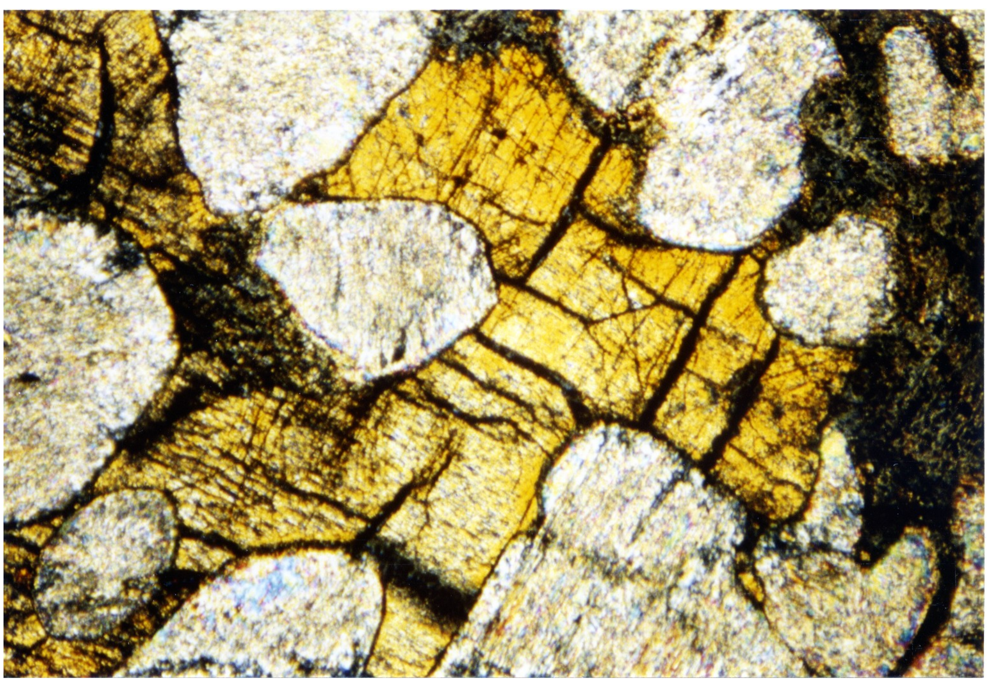


Figure 24
Photomicrograph of websterite from the layered ultramafic sequence. Marginally uralitized intercumulus clinopyroxene (yellow) poikilitically encloses rounded, completely steatized, cumulus orthopyroxene. (crossed polars, short dimension of photograph equals 7 mm).

occurring along their margins. Augen of serpentine between cross-fiber veins consist of colorless to pale green serpentine occurring either as netlike aggregates of sheaflike antigorite, radially arranged, fine fibrous serpentine, or massive, structureless serpentine. The same habit is generally seen everywhere in one slide. Augen consisting of radial fibers occasionally contain small clusters of highly birefringent, fine-grained talc in their centers.

Orthopyroxene occurring in layered ultramafic rocks is also extensively altered. Only one thin-section examined contains orthopyroxene grains with unaltered enstatite cores; all others contain only totally altered grains. These occur predominantly as 0.5 to 5 mm, anhedral to subhedral grains (Figures 23 and 24). Euhedral grains with characteristic octahedral cross-sections are less common (Figure 25).

Orthopyroxene exhibits a variety of alteration products. Serpentine is the most abundant and commonly occurs as colorless to pale green, weakly birefringent, slightly pleochroic antigorite pseudomorphs (bastite). These show a well-developed cleavage or alignment of fibers parallel to the original {110} pyroxene cleavage direction. Serpentine is also seen as irregular patches of bladed, colorless, mesh-texture antigorite, as very fine-grained serpentine intergrown with talc, and as rare cross-fiber chrysotile veins. Talc is a fairly commonly observed alteration product and occurs as very fine-grained, colorless to pale green aggregates, commonly intergrown with serpentine. Larger platy grains are seen in some cases. Tremolite is the only other alteration mineral seen, and appears in minor amounts in a restricted number of samples. It forms aggregates of small, colorless, prismatic grains, and also occurs as isolated, strongly aligned, prismatic to fibrous grains seen in the cores of some orthopyroxenes.

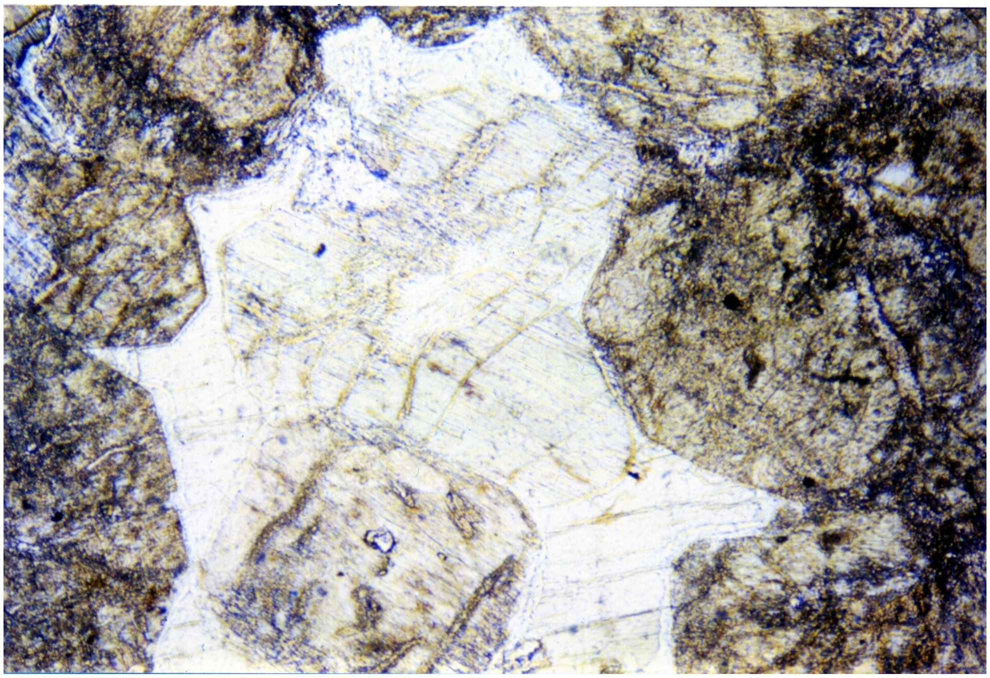


Figure 25

Photomicrograph of completely steatized, euhedral, cumulus orthopyroxene (green-brown) adjacent to completely chloritized intercumulus plagioclase (colorless) in plagioclase-bearing orthopyroxenite from the layered ultramafic sequence (plane light, short dimension of photograph equals 1.7 mm).

amphibole is seen. Alteration usually proceeds from grain margins inward, and is generally less complicated than that seen in orthopyroxene. Tremolite-actinolite occurs as prismatic to fibrous aggregates which rim clinopyroxene and occasionally grow into surrounding igneous grains, obscuring their boundaries. These aggregates often contain abundant fine-grained, disseminated magnetite. In a few intensely serpentinized rocks clinopyroxene is marginally or totally altered to serpentine, usually in the form of bastite pseudomorphs. These look almost identical to bastite pseudomorphs after orthopyroxene, but textural relationships and the presence of relict cores in a few grains show them to be clinopyroxene. Minor amounts of strongly pleochroic brown hornblende are associated with clinopyroxene in a few samples. This occurs most commonly as rims surrounding clinopyroxene grains and is rimmed in turn by colorless tremolite-actinolite in nearly all cases. Hornblende rims are sometimes discontinuous, with tremolite-actinolite outer rims contacting clinopyroxene where hornblende is absent. This hornblende may be a primary, late-stage igneous mineral or an alteration product of clinopyroxene. Petrographic textural relationships do not provide enough evidence to make this distinction.

Accessory minerals seen in ultramafic rocks are restricted to chromite and magnetite, which never occur in modal concentrations greater than 1%. Chromite is the most abundant of these and occurs in two distinct forms. Most ultramafic rocks contain small chromite grains that do not exceed 0.1 mm across. These occur both as anhedral grains and euhedral octahedra. Most are nearly opague, although thin edges and thin grains are slightly translucent and dark brown. Thin opaque rims of magnetite commonly surround translucent grains. Many ultramafic rocks from area E near Betts Big Pond contain large, highly irregular chromite grains that are considerably more translucent than those seen in other areas and have a very characteristic deep reddish-brown color. These usually have magnetite rims similar to those surrounding chromite from other areas. The significance of this bimodal distribution of chromite types has been discussed in the preceding chapter.

The presence of plagioclase in Betts Cove ultramafic rocks is difficult to ascertain in most cases as it appears to be very susceptible to alteration. Recognizable plagioclase is seen in several samples, but in most is totally altered to other phases. Where recognized it usually occurs as irregular 0.1 to 2 mm interstitial grains. Optical determinations indicate that existing plagioclase is usually very close to albite in composition, being less than An_{10} in all cases. Original plagioclase was probably much more calcic than this.

Although it is totally altered in most cases, there is good evidence for the existence of plagioclase as a primary mineral in many of the ultramafic rocks. Recognizable grains showing marginal alteration are always altered to pale green chlorite, occurring either as large blades or as extremely fine-grained, nearly isotropic aggregates. Interstitial chlorite seen in rocks containing no recognizable plagioclase shows very similar habits and optical characteristics, and it is believed to represent completely replaced primary plagioclase (Figure 25). In some samples exhibiting well preserved igneous textures and recognizable mafic phases, chlorite of this type occurs as well-defined interstitial patches with sharp margins. It is clear from textural and metamorphic evidence that this chlorite represents the alteration product of a separate igneous phase, plagioclase being the most likely candidate considering the rock types involved. In addition, highly resorbed cumulus olivine and orthopyroxene grains in some samples show very irregular margins where in contact with clinopyroxene (Figure 23), but euhedral outlines against patches of fine-grained chlorite (Figure 25). Jackson (1961) describes nearly identical textural relationships in unaltered cumulate rocks from the Stillwater Complex in Montana. Unaltered plagioclase in these rocks plays the same textural role as do the chlorite pseudomorphs in the Betts Cove examples (see Jackson, op. cit., Figure 55). In addition, similar metasomatic chloritization of plagioclase has been reported by Miyashiro et al. (1979) from Mid-Atlantic Ridge gabbros.

Original igneous textures are well preserved in most of the ultramafic rocks. Mesoscopic features described in the following chapter indicate that many of these rocks are of cumulate origin. Most display microscopic textures similar to those commonly seen in cumulate rocks as described by Jackson (1961) and Wager, Brown, and Wadsworth (1960). Although recent work (McBirney and Noyes, 1979) indicates that similar textures may occur in rocks produced by processes which are not generally considered to be of a cumulate nature, the textural terms applied to them are useful for descriptive purposes.

Textural relationships are very consistent among the majority of the samples examined in thin section. In nearly all cases olivine, orthopyroxene, and chromite occur as cumulus phases. Clinopyroxene and plagioclase occur as intercumulus phases and occupy interstices between cumulus grains (Figures 23, 24, and 25).

Textural variations in Betts Cove ultramafic rocks appear to be largely a function of differences in the processes affecting cumulus grains after their deposition. A rather small percentage of these rocks contain subhedral to euhedral cumulus grains which have apparently been little-affected by post-depositional processes. These constitute a relatively close-packed framework surrounded by moderate amounts of interstitial material. This texture is very similar to the automorphic-poikilitic texture of Jackson (1961). A larger number of samples contain anhedral, equidimensional cumulus grains which occur in a fairly tightly-packed framework with minor intercumulus material. This texture is most similar to the adcumulate texture of Wager, Brown, and Wadsworth (1960) or the xenomorphic texture of Jackson (1961). In this case growth of cumulus grains has presumably occurred after deposition on the magma chamber floor. An equally large proportion of samples show textures characterized by the resorption and embayment of cumulus grains occurring as the result of reaction between cumulus grains and melt, as described by Jackson (1961). This reaction is usually localized in small areas on a thin-section scale, producing spongy oikocrysts of intercumulus material surrounding very irregular anhedral cumulus grains (Figure 23). During this reaction olivine and orthopyroxene cumulus phases are replaced by clinopyoxene in nearly all cases. Many of the ultramafic rocks of area E and one sample of harzburgite occurring as an irregular xenolith in area A (Figure 14) contain large orthopyroxene oikocrysts enclosing and replacing olivine grains, but were the only samples seen displaying such relationships. The origins of both the xenolith and the area E ultramafics is unclear, but this textural similarity suggests that they may be related (see Section 3F). Rocks displaying reaction textures which are locally developed on a thin-section scale may show either automorphic-poikilitic or xenomorphic/

Orthopyroxene commonly exhibits complex alteration relationships. Different alteration phases may occur consistently in the cores and rims of all the grains of one sample, but alteration relationships are confusing and inconsistent when comparisons are attempted between samples. Antigorite pseudomorphs after orthopyroxene form the cores of the majority of grains examined. Rimming these can be found mesh-texture antigorite, fine-grained aggregates of talc with or without serpentine, or tremolite. Grains often have several irregular, roughly concentric rims, each consisting of different phases. Bastite cores are homogeneous in most cases, but may contain clusters of sliverlike tremolite or large, platy talc grains in their centers. Some grains are completely homogeneous and consist entirely of bastite or talc and serpentine.

Clinopyroxene is found in a variety of sizes, shapes, and degrees of alteration. It commonly occurs as irregular, 0.2 to 3 mm grains interstitial to rounded olivine and orthopyroxene grains. It is also seen as larger grains, forming optically continuous, rounded oikocrysts up to 3 cm across which surround and include smaller cumulus orthopyroxene and olivine grains (Figure 23). Tabular clinopyroxene grains occurring in pegmatitic clinopyroxenite dikes commonly exceed 3 cm in length. Examples of these dikes occurring near Pittman Bight in places contain individual clinopyroxene grains up to 30 cm long. Optical characterisitics indicate that unaltered clinopyroxenes in ultramafic rocks are generally diopsidic in composition and sometimes contain fine exsolution lamellae of altered orthopyroxene.

Completely unaltered clinopyroxene is not uncommon, but, in most cases, partial alteration to a colorless to green tremolite-actinolite adcumulate textures in areas in which reaction has not occurred.

C. Gabbros and Related Mafic Plutonic Rocks

The gabbroic rocks of the Betts Cove ophiolite complex occur primarily as a thin and somewhat discontinuous sequence above the ultramafic rocks comprising the structurally lowest unit of the ophiolite. In many places this gabbroic sequence can be divided into a lower relatively well-layered zone containing interlayered ultramafic rocks and an upper, poorly layered to homogeneous zone. The gabbroic rocks of these two zones are similar in many respects, but exhibit a number of important differences in composition and alteration. For this reason the general characteristics of gabbroic rocks from each of these zones are described separately below.

1. Gabbros from the Layered Ultramafic and Interlayered Units

Layered gabbroic rocks comprising the lower portion of the plutonic sequence are predominantly gabbronorites, with gabbros and norites accounting for most of the remainder (Figure 26). Both leucocratic and melanocratic varieties of these types are common. Olivine-bearing gabbroic rocks such as olivine gabbronorites, olivine gabbros, troctolites, and related gabbroic rocks containing greater than 10% olivine are quite rare. These layered gabbroic rocks are generally medium- to coarse-grained, though isolated microgabbro layers occur in some places.

The layered gabbroic rocks show large differences in appearance in the field, depending primarily upon their composition and state of alteration. Melanocratic varieties rich in clinopyroxene appear grey or green, while those rich in orthopyroxene generally weather to brown or reddish-brown colors. Leucocratic gabbroic rocks appear medium to light grey, with anorthositic and highly altered samples appearing chalky white.

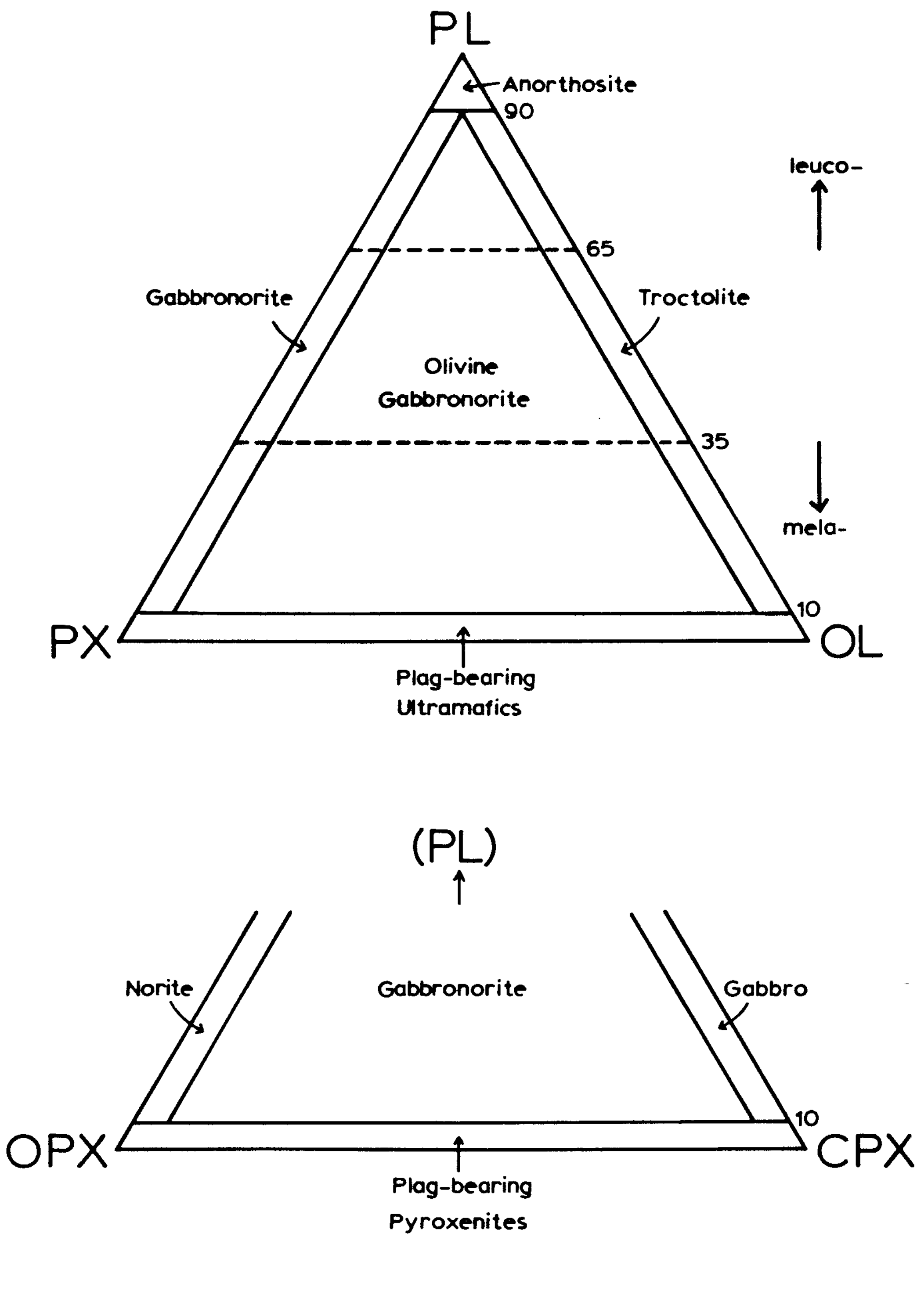


Figure 26

Classification scheme used for Betts Cove gabbroic rocks.

Fresh surfaces vary from dark grey or green to pale grey or white with increasing plagioclase content.

Mafic minerals in these rocks generally have appearances similar to those in the ultramafic rocks described previously. Plagioclase commonly appears as light grey to chalky white grains which usually weather in relief relative to mafic minerals surrounding them. Many samples contain partially to completely chloritized plagioclase, which weathers to a reddish-brown color and is easily mistaken for orthopyroxene or olivine in the field. Saussuritized plagioclase grains generally appear similar to relatively fresh grains, although they are usually slightly greenish in color.

Original igneous phases seen in relatively unaltered samples consist predominantly of plagioclase, clinopyroxene, and orthopyroxene, with minor olivine, magnetite, and chromite (Figure 27). Most samples collected show moderate to extensive alteration, however, hindering classification and in some cases totally obscuring the original textures and mineralogy.

The dominant mafic phase in most of the layered gabbroic rocks examined in thin section is clinopyroxene, which generally comprises 30 to 75% of these rocks. It usually exhibits similar textural and alteration characteristics in both layered gabbroic and ultramafic rocks, occurring in the layered gabbros as anhedral to euhedral grains 0.2 to 4 mm across (Figure 27). Optical properties suggest that it is diopside or augite in most samples.

The most common alteration product of clinopyroxene is actinolite. It occurs as pale green rims and in some cases completely replaces original grains. In some samples the original grain boundaries of totally

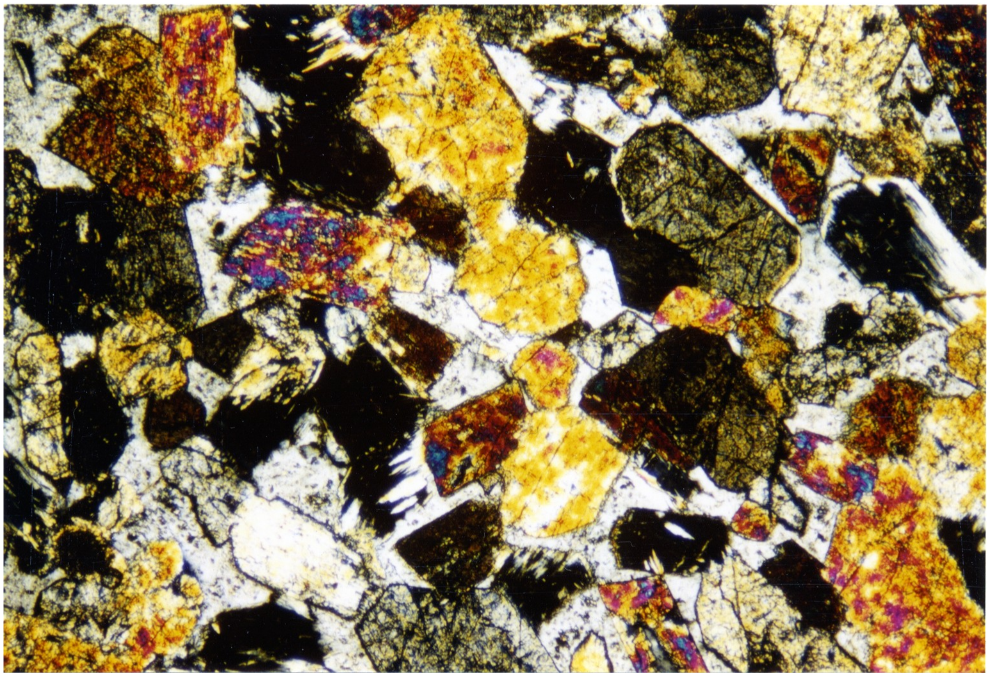


Figure 27

Photomicrograph of gabbronorite from the interlayered sequence. Euhedral, marginally uralitized clinopyroxene (moderately birefringent) and serpentinized orthopyroxene (dark brown to black) grains are surrounded by slightly chloritized interstitial plagioclase (colorless). (crossed polars, short dimension of photograph equals 1.7 mm).

altered clinopyroxene grains are faithfully preserved, although metamorphic overgrowth obscures original boundaries in most cases and is generally more extensive in these rocks than in the ultramafic rocks. In a few samples blue-green hornblende and more rarely brown hornblende replace clinopyroxene. Hornblende was distinguished from actinolite in these samples primarily by extinction angle and color, although in some cases it was difficult to make this distinction, as the optical properties of these two amphiboles are gradational. Hornblende generally displays the same replacement relationships as actinolite. Much of it appears to be of metamorphic origin based on textural evidence. Hornblende overgrowths and isolated prismatic hornblende grains in these samples commonly cross-cut boundaries between igneous grains and display metamorphic textural relationships along their margins. In some thin sections insufficient textural evidence exists to determine the origin of the hornblende present, allowing the possibility that some hornblende present in these rocks is of igneous origin.

Orthopyroxene is generally less abundant than clinopyroxene, commonly comprising 5 to 60% of the layered gabbroic rocks. It occurs as 0.5 to 4 mm grains which are usually subhedral to euhedral (Figure 27). Orthopyroxene is totally altered in all of the layered gabbros examined in thin section, but it can usually be identified by its distinctive alteration. In gabbroic rocks immediately above the basal layered ultramafic sequence orthopyroxene is usually altered to pale green, weakly birefringent antigorite pseudomorphs (bastite) (Figure 27) similar to those seen in the underlying ultramafic rocks described in the preceding section. In the remainder of the layered gabbroic rocks orthopyroxene alters largely to green pleochroic chlorite, which usually forms pseudomorphs similar to those of antigorite. In a few examples orthopyroxene is replaced by fine-grained aggregates of flaky chlorite which faithfully preserve original euhedral orthopyroxene grain boundaries. Chlorite pseudomorphs after orthopyroxene are sometimes rimmed by fibrous actinolite, which replaces entire grains in highly uralitized rocks.

Olivine is generally rare in rocks containing appreciable amounts of plagioclase. It usually occurs as widely scattered, subhedral, 0.5 to 5 mm grains which are totally serpentinized and generally similar in appearance to those occurring in the ultramafic rocks.

Gabbroic rocks from the lower layered sequence contain from 10% to 75% plagioclase. This occupies a variety of textural positions relative to mafic grains, occurring as small, irregular, interstitial grains in some samples (Figure 27) and euhedral laths up to 7 mm long in others. Optical measurements of albite twin extinction angles on relatively "fresh" grains show a consistent clustering of compositions at or near An_{10}. The type and abundance of mafic minerals within these rocks suggest that they were originally gabbros and probably contained original plagioclase which was more calcic than An_{50}. Low-grade metamorphism has apparently albitized all of this original plagioclase.

In addition to this compositional change, most plagioclase grains have undergone other alteration, of which two main types are seen. In some samples plagioclase grains have been partially to completely chloritized in a manner similar to that seen in the ultramafic rocks. Chlorite appears in partially chloritized grains as irregular, pale green patches giving the grains a "moth-eaten" appearance. Totally chloritized grains are usually recognizable only by examining textural relationships and alteration in the other phases present. In most other samples plagioclase has been altered (saussuritized) to clinozoisite, epidote, and sericite, occurring as clusters of small grains concentrated in the cores of plagioclase laths. As with other types of alteration in the Betts Cove plutonic rocks, varying amounts of alteration, from incipient to total, are found.

In many layered gabbro samples original igneous textures are largely destroyed by metamorphic overgrowth. Igneous textures were clearly observed in some samples, however, with two main types recognized. In some samples plagioclase occurs as irregular intercumulus grains interstitial to cumulus mafic phases (Figure 27). These rocks generally exhibit textures similar to those occurring in the underlying layered ultramafic rocks. Other samples show ophitic to subophitic textures characterized by subhedral to euhedral plagioclase laths surrounded by interstitial clinopyroxene. Where present, orthopyroxene and olivine also appear to occur as subhedral grains partially surrounded by clinopyroxene. The distribution of these two textural types is unclear, although rocks exhibiting the first types appear to be most abundant in the layered ultramafic unit and lower portion of the overlying interlayered unit.

2. Gabbros from the Homogeneous Gabbro and Sheeted Diabase Dike Units

Weakly layered to homogeneous gabbroic rocks occur above the layered gabbros in many places, and in some areas occur as isolated screens between sheeted diabase dikes. These consist predominantly of gabbro and leucogabbro, with minor amounts of melagabbro and clinopyroxenite (Figure 26). They tend to weather pale grey to white in the field, with very leucocratic and highly altered varieties appearing chalky white. Broken surfaces are generally greenish in color, presumably reflecting the abundance of alteration phases present in most samples.

Plagioclase is readily recognizable in these rocks as it weathers chalky white with few exceptions. Mafic minerals (dominantly clinopyroxene) are almost always rimmed by actinolite or hornblende. These are readily distinguishable in most cases as actinolite appears bright green, while hornblende is usually dark brown to black. Quartz forms grey, glassy grains which weather with marked relief.

Most of the homogeneous gabbroic rocks are intensely altered. This alteration is generally more intense and pervasive than that affecting the underlying layered gabbros. In many cases alteration is so extreme that it is impossible to assign an igneous rock name to some samples; these are simply classified as metabasites (Figure 28). Less-altered samples contain 30 to 80% albitized plagioclase, 20 to 70% clinopyroxene, and minor amphibole as relic igneous phases, although these are usually marginally altered. Orthopyroxene appears to be extremely rare and was not positively identified in any of the samples examined in thin section. It is possible that completely altered orthopyroxene appears similar to altered clinopyroxene in these rocks, making distinction between the two difficult or impossible. This is unlikely, however, as orthopyroxene was absent in all partially altered samples in which all of the original mafic phases could be identified. Olivine was not observed in any thin sections of these rocks.

Clinopyroxene occurring in samples with partially preserved igneous textures usually occurs as 0.2 to 2 mm irregular grains interstitial to

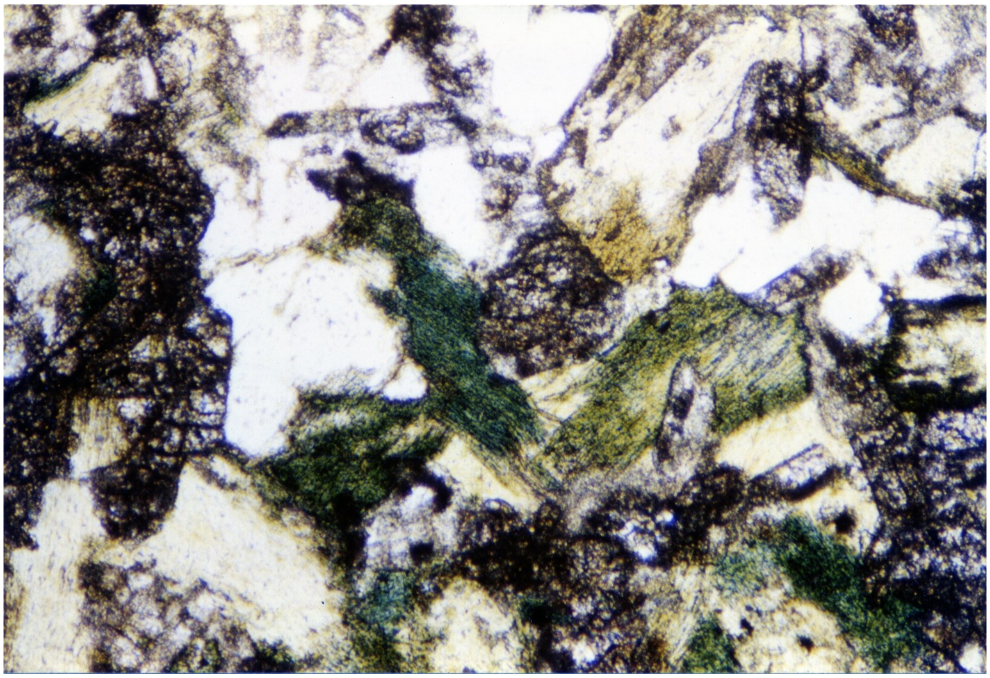


Figure 28

Photomicrograph of metabasite from the homogeneous gabbro unit. Blue-green hornblende is partially replaced by chlorite (pale yellow-green), large quartz grains partially enclose turbid, brown, saussauritized plagioclase laths (plane light, short dimension of photograph equals 1.7 mm).

other phases. It is usually partially to completely altered to blue-green hornblende or fine, fibrous aggregates of actinolite and chlorite. Some samples show both of these types of alteration; in these blue-green hornblende usually forms the outermost alteration rim.

Plagioclase occurs in thin section as subhedral to euhedral, 0.5 to 4 mm laths with compositions ranging from An_5 to An_{15}. These sodic compositions may reflect original igneous compositions, or, more likely, may be the result of albitization of more calcic igneous plagioclase. The abundant evidence of intense low-grade metamorphism in most of these rocks lends considerable support to the latter hypothesis, although the presence of igneous amphibole in a small number of samples suggests that they may be diorites rather than gabbros, allowing the possibility of the former hypothesis. Differentiating between original diorites and gabbros among the rocks of this group is probably impossible, however, as no additional and more conclusive evidence exists for the origin of the plagioclase they contain.

Plagioclase grains are commonly saussuritized in a manner similar to that seen in gabbroic rocks of the interlayered unit (Figure 28). Sericite, clinozoisite, and epidote are the most abundant products of this alteration. Epidote is much more common in the isotropic gabbros than in the lower layered sequence.

Small, highly corroded and altered amphibole grains are present in small quantities (up to 5%) in two samples examined in thin section. These are believed to represent original igneous amphibole grains, as they have a very different appearance from most of the amphibole grains occurring in these rocks, which are clearly of metamorphic origin. In some places these corroded amphibole grains have been partially overgrown by metamorphic blue-green hornblende. They are usually intensely altered to an unidentifiable, amorphous, brown alteration product and are recognizable only by their distinctive grain shapes and cleavage.

Only a few thin sections of the homogeneous gabbroic rocks exhibit recognizable igneous textures. These are generally sub-ophitic to ophitic, with euhedral plagioclase laths partially to completely surrounded by clinopyroxene. A vast majority of the samples examined are intensely altered and exhibit metamorphic textures produced by static recrystallization and characterized by a complete absence of any tectonic fabric. The most highly altered rocks are metabasites, consisting of interlocking grains of saussuritized plagioclase and hornblende, with variable amounts of quartz, epidote, clinozoisite, carbonate, and sericite (Figure 28).

The presence of quartz in some homogeneous gabbroic rocks is noteworthy as it is readily recognizable in the field in places and comprises up to 35% of some samples. It generally occurs as clusters of large, optically continuous, anhedral grains cut by irregular cracks which are usually filled with epidote and chlorite (Figure 28). In some samples well-developed myrmekitic intergrowths of quartz and plagioclase are common. The restriction of quartz to only the most altered samples, and its close textural association with metamorphic phases strongly suggest that most, if not all, of the quartz present in the Betts Cove gabbroic rocks is of metamorphic origin. Similar occurrences of quartz in altered gabbroic rocks from Chilean ophiolites are described by Stern et al. (1976), who also suggest that it is a product of metamorphism.

D. Diabase Dikes

Variably altered diabase dikes cut all of the rocks of the Betts Cove ophiolite. Most of these dikes appear to be related to and of the same age as the dikes comprising the sheeted dike unit. A small number of later dikes cross-cut these early dikes and are recognizable in the field by their distinctive colors, weathering characteristics, and orientations.

1. Early Dikes

Diabase dikes belonging to the earlier set are best-developed in the sheeted dike unit, but occur sporadically in the gabbroic and ultramafic rocks. They are readily recognizable in the field by their distinctive reddish-brown and green weathering colors. The distribution of dikes displaying each of these weathering colors appears to be random throughout the areas where early dikes occur. In most cases these weathering colors reflect both variations in original composition and extent of alteration affecting the dikes. Those displaying reddish-brown colors generally contain chlorite as the dominant alteration phase, while the green-weathering dikes are usually rich in actinolite. Weathering colors often vary along the length of individual dikes, suggesting that the color difference is not due to original compositional differences in all cases. In areas where sporadic diabase dikes cut ultramafic and gabbroic rocks the type of alteration (and hence the weathering colors) tends to mimic that occurring in the surrounding rocks.

Early diabase dikes are generally fine-grained to aphanitic, and in most cases are aphyric. Some dikes contain isolated phenocrysts 3 mm to 3 cm across, which in rare cases comprise up to 30% of the rock. These almost always weather more intensely than the surrounding groundmass, forming prominent pits on weathered surfaces. The identification of these phenocrysts in the field is extremely difficult due to their high state of alteration; many attempted field identifications were proven incorrect by subsequent thin section examination, discussed below.

Chilled margins usually occur on isolated dikes cutting coarse-grained plutonic rocks. Dikes occurring within the sheeted dike unit commonly show one or no chilled margins. These are presumably parts of dikes older than adjacent dikes that are chilled against them.

Rare examples of internally brecciated early diabase dikes occur in some areas, predominantly within the sheeted dike unit. These consist of rounded, 1 cm to 5 cm clasts comprising 50 to 80% of the total dike surrounded by rusty, highly altered, fine-grained matrix material.

The rock comprising these early dikes is with few exceptions intensely altered at all levels within the ophiolite. Examination of the least-altered samples of dike rock collected suggests that most of these were originally diabases, although some picritic dikes were found. In most samples the determination of original igneous composition is impossible.

Microscopic examination of early dike samples shows that most of them consist of aggregates of 0.1 mm to 0.5 mm amphibole and chlorite grains (Figure 29). The amphibole present occurs as bladed, prismatic grains, and is usually colorless tremolite in dikes cutting ultramafic rocks, while pale green actinolite generally occurs in dikes from the gabbroic and sheeted dike units. In portions of the gabbroic units where hornblende occurs in the plutonic rocks some dikes contain pale brown to blue-green hornblende as the dominant amphibole. Chlorite generally

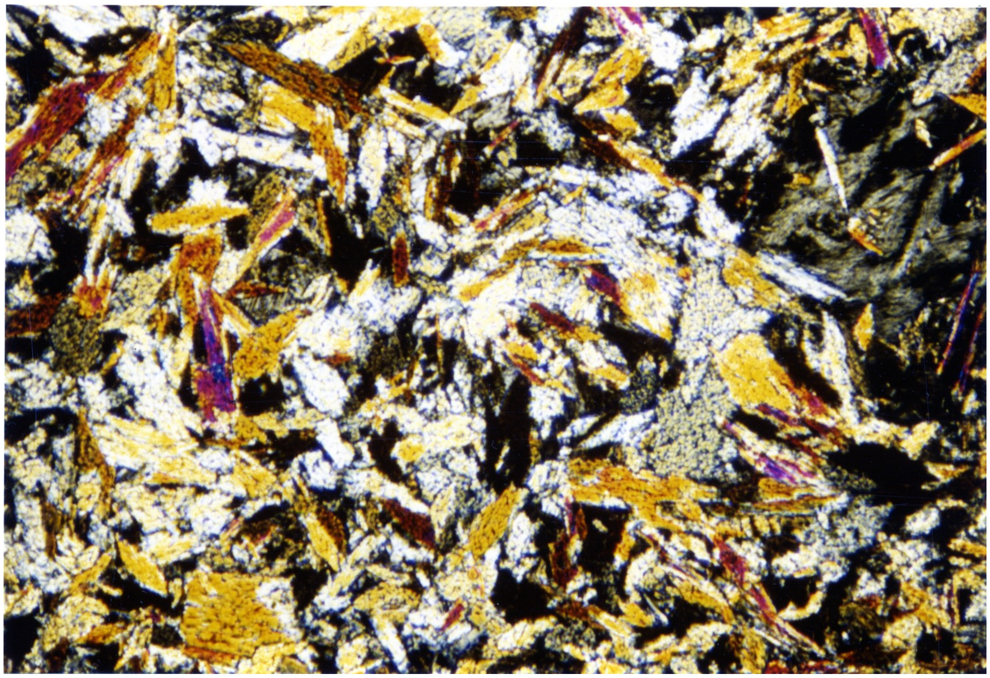


Figure 29

Photomicrograph of matrix of altered early diabase dike. Chlorite (dark patches) occurs interstitial to bladed tremolite (moderately birefringent). (crossed polars, short dimension of photograph equals 1.7 mm).

occurs as large, irregular, pale green grains commonly displaying anomalous birefringence colors or as aggregates of minute flakes which appear nearly isotropic. In most samples chlorite grains occupy positions interstitial to prismatic amphibole grains, the overall texture being best-described as decussate.

In a few less-altered samples plagioclase occurs as irregular grains partially replaced by chlorite. These occupy the same textural positions as the irregular chlorite grains occurring in highly altered samples, suggesting that much of the chlorite in these may be an alteration product of plagioclase. Chlorite generally occurs as irregular, vermicular patches within plagioclase and appears to replace the outer portions of plagioclase grains first. Optical determination of plagioclase compositions were not possible in these samples due to the small size and partial alteration of the grains. No identifiable igneous mafic phases (presumably pyroxene?) were identified in any of these least-altered samples.

Accessory minerals present in many early dike samples include quartz, sphene, epidote, clinozoisite, and carbonate. These occur in very small quantities, generally comprising a much smaller portion of these rocks than they do of the gabbroic rocks.

Phenocrysts in porphyritic dike samples are extensively altered and difficult to identify in thin section. Well-preserved grain outlines aid in the identification of some phenocrysts, while distinctive alteration is helpful in other cases. When each of these is lacking, identification is often impossible. Plagioclase, olivine, clinopyroxene, and orthopyroxene all appear to occur as phenocrysts, although plagioclase is probably the most abundant. Plagioclase phenocrysts are partially to completely altered to chlorite or quartz-chlorite aggregates.

Olivine phenocrysts are quite distinctive and alter to pale green antigorite cut by irregular cross-fiber chrysotile veins (Figure 30). Some olivine phenocrysts contain large, irregular chromite inclusions. Pyroxene alters most commonly to aggregates of interlocking prismatic tremolite or actinolite grains, which probably represent original clinopyroxene phenocrysts. A small number of phenocrysts display pyroxene cross-sectional shapes and alter predominantly to chlorite (Figure 31). These may have been orthopyroxene phenocrysts.

Some of the early dikes contain abundant olivine and orthopyroxene phenocrysts (up to 40%) and relatively low proportions of plagioclase. These are best described as picritic diabases. The abundance of these relative to the entire dike population is difficult to ascertain as they are not particularly distinctive in outcrop appearance. Since they comprise only a small proportion of the dikes examined in thin section they are, however, probably subordinate to normal diabase dikes. Picritic dikes appear to be most prevalent in the layered ultramafic and sheeted dike units, and less common in the homogeneous gabbros. Normal diabase dikes containing plagioclase and clinopyroxene phenocrysts are present throughout the ophiolite.

Dikes with komatiitic compositions have been reported to occur at various levels within the ophiolite by Upadhyay (1976, 1978) and Coish and Church (1979). Many of the picritic diabase dikes examined in this study have macroscopic and microscopic characteristics similar to those of the dikes described as komatiites by these researchers. Since no chemical analyses were obtained from these dikes, it was imposible to classify them chemically, although crude chemical compositions were obtained by estimating the compositions of the phases present and adding these compositions in amounts proportional to their modal abundances.

Figure 30

Photomicrograph of serpentinized olivine phenocrysts in early picrite dike (plane light, short dimension of photograph equals 7 mm).

Figure 31

Photomicrograph of completely altered orthopyroxene? phenocryst in early picrite dike (plane light, short dimension of photograph equals 7 mm).

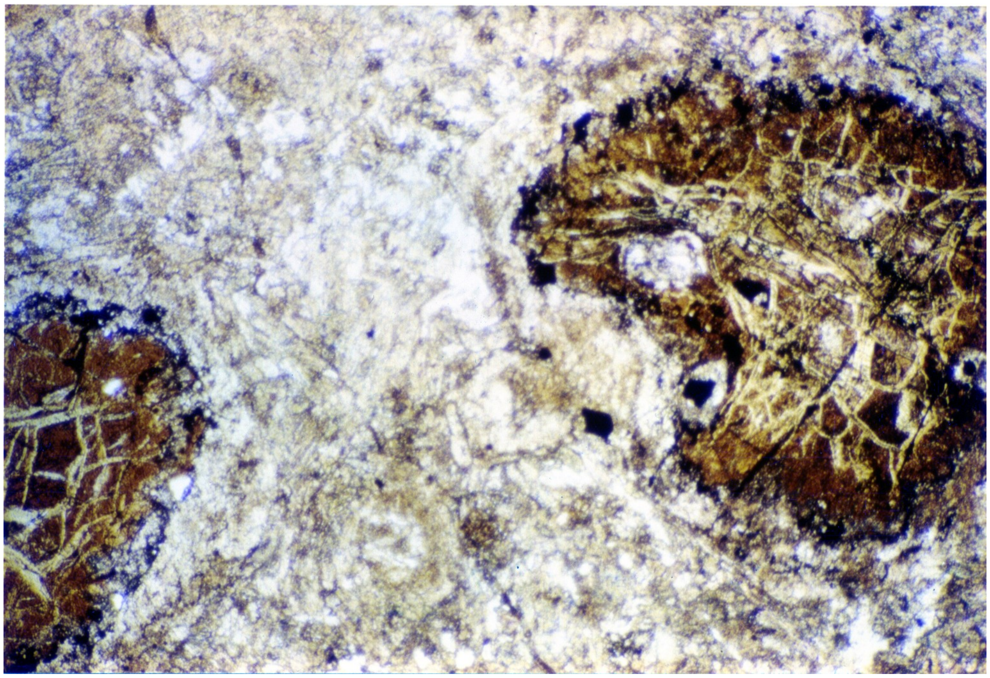


Figure 30
Photomicrograph of serpentinized olivine phenocrysts in early picritic dike. (plane light, short dimension of photograph equals 7 mm).

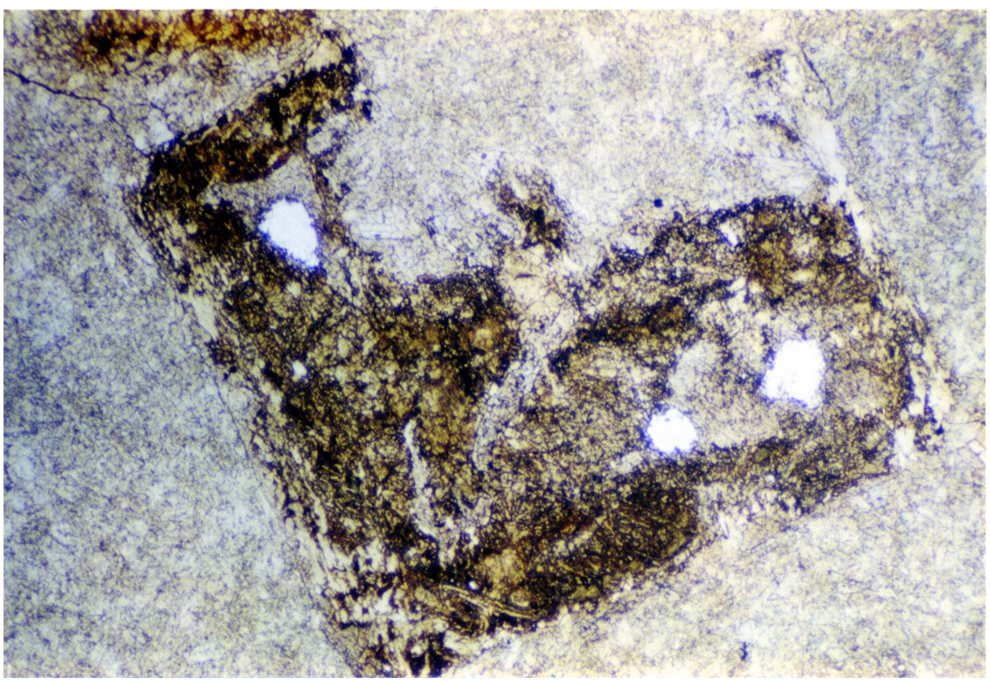


Figure 31
Photomicrograph of completely altered orthopyroxene? phenocryst in early picritic dike. (plane light, short dimension of photograph equals 7 mm).

These tend to confirm the previously reported compositions.

2. Late Dikes

Late diabase dikes are rare, and generally occur along fault zones as isolated dikes cutting highly altered and sheared rocks. However, several were found cutting structurally intact ultramafic and gabbroic rocks. These dikes weather to a distinctive chalky grey color, and commonly contain a penetrative parting parallel with their margins, even in areas where the adjacent rocks contain no parting. They are aphanitic and usually porphyritic, containing up to 35% phenocrysts ranging in size from 1 mm to 1 cm. These phenocrysts are readily recognizable in the field in most cases as pyroxene, an observation confirmed by thin section examination. These dikes usually display well-developed chilled margins, although these are often partially to completely obscured by rodingitization and other types of alteration, especially in areas where late dikes cut ultramafic rocks.

Microscopic examination shows, in most cases, that the late diabase dikes are somewhat less altered than those of the early set (Figure 32). The groundmass of relatively little-altered samples usually consists predominantly of 0.1 to 0.5 mm, tabular plagioclase laths, which have usually been relatively unaffected by chloritization or saussuritization. Clinopyroxene occurs as the other major constituent of the groundmass, and is preserved in the cores of some actinolite and tremolite grains formed from its alteration. Trachytic textures are generally observed in these less-altered samples.

More highly altered samples of late diabase dike rock are usually similar, microscopically, to samples of the early dikes. The groundmass of these generally consists of actinolite or tremolite and chlorite ag-

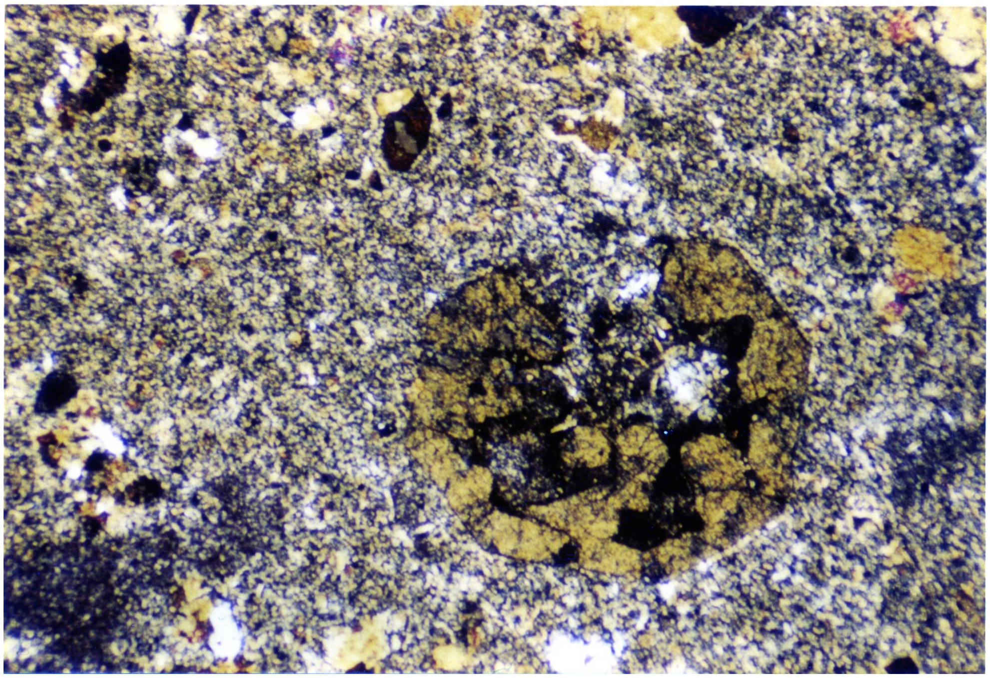


Figure 32

Photomicrograph of a late diabase dike. Groundmass clinopyroxene, actinolite, and plagioclase surround partially replaced, euhedral clinopyroxene phenocrysts. (crossed polars, short dimension of photograph equals 7 mm).

gregates displaying decussate textures. Sphene, epidote, and carbonate are common accessory phases.

Phenocrysts in porphyritic late dikes consist almost exclusively of clinopyroxene (Figure 32). These are usually remarkably unaltered, even in samples with highly altered groundmass phases. They are subhedral to euhedral and in some cases are somewhat embayed. In some samples these clinopyroxene phenocrysts are partially replaced along their margins by aggregates of fine-grained tremolite and chlorite.

E. Highly Altered and Fault-Related Rocks

A small proportion of the rocks occurring in the map areas are highly altered and in some cases deformed, and are derived from the surrounding rocks of the ophiolite. These usually occur within or adjacent to zones of intense faulting within the ophiolite and along its margins. The following types of fault-related rocks occur in the map areas and appear on plate 2:

1. Serpentinite

The term "serpentinite" is used here to describe ultramafic rocks which have undergone serpentinization to the point where the original mineralogy and textures are largely destroyed and no igneous name can be assigned to the rock.

Serpentinite usually occurs within or adjacent to fault zones and often contains a spaced (1 to 10 cm) phacoidal cleavage. Cleavage surfaces usually appear green and waxy and often display prominent slickensides. In thin section this serpentinite is seen to consist almost entirely of serpentine occurring as platy antigorite grains and cross-fiber chrysotile veins. Magnetite occurs as trails of small grains oriented sub-parallel to the phacoidal cleavage and as clusters of grains filling randomly oriented cracks and veins. Small, isolated, slightly translucent to opaque chromite grains occur in minor quantities. Grains displaying relict igneous outlines are rare, although in a few samples large kinked serpentine grains cut by anastomosing chrysotile veins occur and may represent original olivine grains.

More massive serpentinite is also seen and is recognizable in the field by its distinctive blue-grey weathering colors. In general no individual grains can be discerned on weathered surfaces in the field, although in some places totally serpentinized pyroxene? grains weather in relief relative to the serpentine around them, which has presumably replaced olivine grains. Microscopic examination shows this massive serpentinite to consist primarily of anastomosing cross-fiber chrysotile veins, with patches of sheaf-like mesh-texture antigorite occupying interstices between veins (Figure 33). Magnetite occurs as trails of small grains in the centers of chrysotile veins and as larger, isolated grains and clusters. Some samples contain rare, large, irregular antigorite grains, which may be bastite pseudomorphs after pyroxene. Chromite is present in minor amounts, commonly as large, irregular, reddish-brown grains rimmed by magnetite.

2. Rodingite

Rodingite is fairly rare in the Betts Cove ophiolite. It occurs in some areas where rocks of gabbroic composition are in contact with or in close proximity to highly serpentinized ultramafic rocks. Rodingite occurs in the field as small exposures of hard, very fine-grained, light grey to white rock which is quite resistant to weathering. In most samples the grain size is too small to allow petrographic identification of the individual phases present. Microscopic examination of relatively

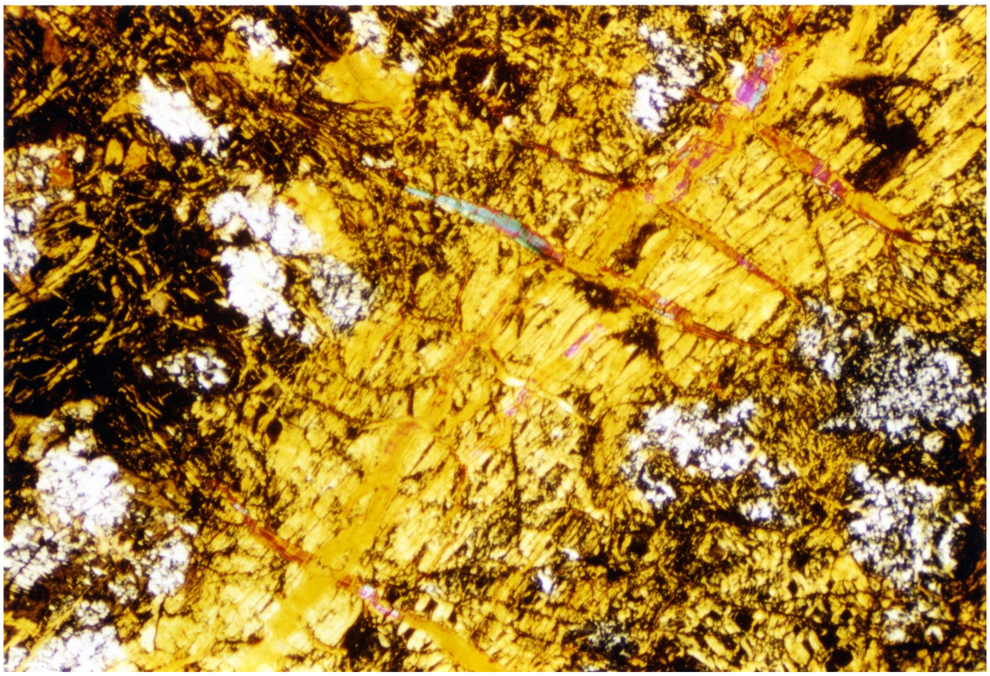


Figure 33

Photomicrograph of serpentine veins and minor talc in massive serpentinite. (crossed polars, short dimension of photograph equals 7 mm).

coarse-grained samples and x-ray diffraction analysis of fine-grained samples indicates that these rodingites consist primarily of diopside, tremolite, hydrogarnet, chlorite, carbonate, and idocrase. All samples examined appear completely recrystallized and display saccharoidal textures.

3. Talc-Carbonate Rock

Talc-carbonate rock occurs in minor quantities as an alteration product of ultramafic rocks in a few areas, and is usually associated with ultramafic-derived breccias (described below). It is a massive, soft, pale blue-grey rock, usually cut by thin (1 to 2 mm), rusty, randomly oriented carbonate veins. It appears in thin section as a fine-grained aggregate of talc, carbonate, serpentine, and magnetite. Actinolite and chromite occur as trace constituents of some samples.

4. Breccias

Breccias derived from gabbroic and ultramafic plutonic rocks occur along fault zones in several areas and are of two types. Breccia interpreted to have been derived entirely from gabbroic rocks (based upon field relationships) is the most common of these. It consists of fine- to medium-grained, pale brown to grey clasts set in a fine-grained, rusty matrix. The clasts are generally well-rounded, 1 cm to 10 cm across, and comprise 30 to 90% of the total rock. In thin section both clasts and matrix are seen to consist of fine-grained aggregates of quartz and chlorite, with quartz being the major constituent of the clasts and chlorite the major constituent of the matrix (Figure 34). This mineralogy is probably the result of intense metasomatic alteration of the original gabbroic rock from which the breccia was derived.

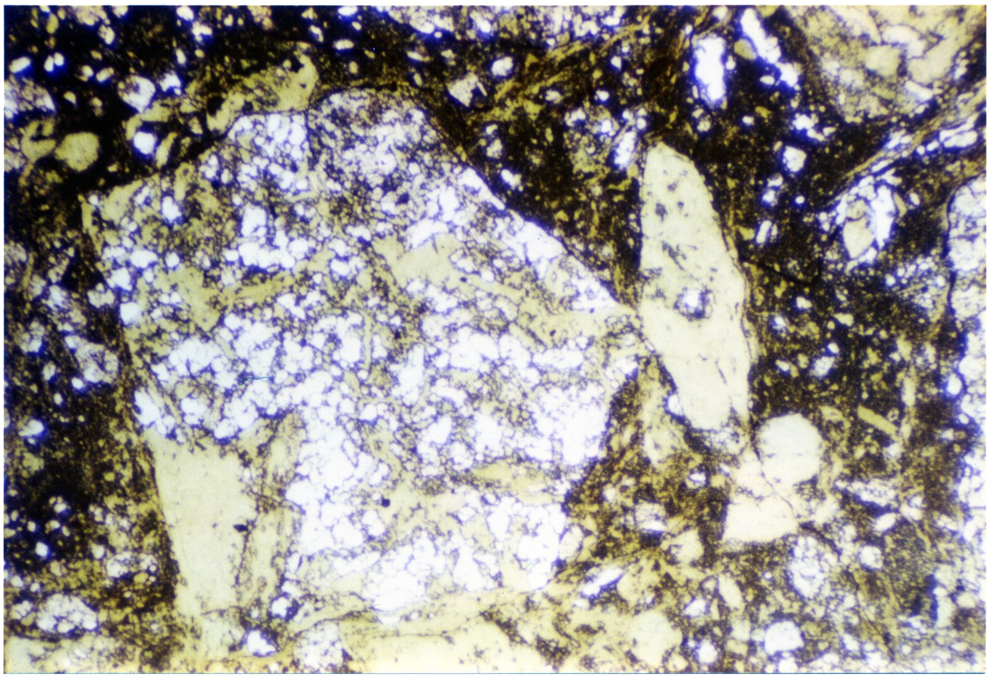


Figure 34

Photomicrograph of altered gabbroic breccia. Small clast of quartz and lesser chlorite sits in a matrix of predominantly chlorite. (plane light, short dimension of photograph equals 7 mm).

Similar breccia, interpreted to have been derived from both gabbroic and ultramafic plutonic rocks, occurs in area D south of Betts Big Pond. This rock is similar to the gabbroic breccia described above, but contains clasts consisting of tremolite and chlorite, some of which contain small, irregular chromite grains.

F. Igneous and Sedimentary Rocks Adjacent to the Ophiolite

Two main lithologic assemblages occur in fault contact with the Betts Cove ophiolite in the northwest portion of the map area (plate 2). These were not examined in detail, but are described briefly below.

1. Sedimentary and Volcanic Rocks

A sequence of mafic volcanic and sedimentary rocks outcrops south of Betts Big Pond in the northwest portion of the map area. These consist in this area of interbedded mafic pillow lava, mafic breccia, coarse-grained volcaniclastic greywacke, and grey, red, and black argillite and chert. This sequence was originally mapped in this area by Upadhyay (1973) as part of the Beaver Cove Group of Dewey and Bird (1971). Correlation of the Beaver Cove and Snooks Arm Groups by Neale *et al.* (1975) allows this sequence of volcanic and sedimentary rocks to be considered as part of the Snooks Arm Group.

2. Quartz-feldspar Porphyry

Grey silicic porphyry occurs in fault contact with the ophiolite to the south of the volcanic and sedimentary rocks described above. It is coarse-grained and consists primarily of quartz, plagioclase, and alkali feldspar, along with minor mafic minerals. This porphyry was referred to as the Burtons Pond Porphyry by Snelgrove (1931). It is similar in most respects to the Cape Brule Porphyry which occurs to the northwest of the Betts Cove ophiolite (DeGrace et al., 1976) except that, unlike the Cape Brule Porphyry, it is virtually undeformed in this area.

CHAPTER V

STRUCTURE

The Betts Cove ophiolite lies on the west limb of a slightly overturned, northeast-plunging syncline which folds all of the rocks of the Snooks Arm Group (Upadhyay, 1973). The ophiolite is dissected by a number of steep faults, dividing it into areas which contain little variation in structure. Five such areas (A through E, see Section 3A) were mapped in detail during the course of this study. Tectonic structures within these areas are restricted to faults, which in most cases appear to have relatively small displacements, and several large-scale folds. These structures are discussed separately in the following sections.

A. Faults

Two prominent fault sets occur in the Betts Cove area. The dominant set has an east to northeast strike and is approximately parallel with the long, northeast-trending fault defining the western edge of the ophiolite (plate 1). Faults belonging to this set are numerous and closely spaced adjacent to this western edge (plate 2), and generally become less common and more widely spaced to the southeast. A subordinate fault set with northwest trends is also observed.

Faults from both of these sets are nearly always subvertical where they occur in outcrop. They generally have very straight map traces (plate 1), suggesting that they are quite steep on a large scale. In rare cases steep,straight faults cut irregular topography having slope dips approximately equal to those of the fault surfaces, resulting in sinuous fault traces in map view (i.e. the prominent east-west trending faults cutting area D (see plate 2). The sense of offset on the faults within the map area is difficult to determine because three-dimensional exposure is usually lacking within fault zones, and the locations and orientations of many distinctive markers within the ophiolite (i.e. unit contacts) are poorly known. It has been suggested that the prominent fault defining the western side of the complex is a steep, west-dipping thrust fault (G. Cockburn, pers. comm. to Church and Riccio, 1974). If so, the intense, northeast-trending faulting adjacent to this edge of the complex may represent a zone of imbrication along which rocks of the Fleur de Lys terrain were thrust toward the east over the ophiolite. The present steep attitude of these faults could be explained by invoking rotation subsequent to their formation. Although the interpretation of these faults as thrusts is quite speculative, it is compatible with steep, east-directed thrusting known to occur to the west in the Baie Verte area (Kidd, 1977; Kidd, et al., 1978) and to the east in Notre Dame Bay (Dean and Strong, 1977).

Some of the faults cutting the ophiolite show evidence of having had complex senses of displacement. One example is the northwest-trending fault separating areas A anc D (plate 2). Unit contacts within these two areas appear to be similarly dipping, but have perpendicular strikes; they may be restored to the same orientation by a 90^{o} rotation about a vertical axis. This rotation could not have resulted along this fault by simple translational slip and must have involved more complex types of fault displacement (assuming that the motion along the fault has not been so great as to have brought areas A and C together from widely separated sites of origin). Two possible methods of accomplishing the required rotation include movement along curved fault surfaces, and rotation and tilting of one block relative to the other within the plane of the fault. The latter mechanism appears more likely, as little evidence for curved faults exists within the ophiolite.

Most of the faults in the Betts Cove area appear as prominent lineaments on aerial photographs. Many of the larger faults are expressed in the field as narrow gullies, within which the exposure is usually poor.

Where faults cut ultramafic rocks, the rocks within and adjacent to the zones of faulting are often intensely serpentinized. Fault zones in these areas are often quite wide (5 to 10 m), and the serpentinite within them contains a well-developed phacoidal cleavage in places (Figure 35). The fault zones and the cleavage within them are usually coplanar. Rodingitized diabase dikes cut fault-zone serpentinite in several places and are chilled against the serpentinite (Figure 35). This relationship suggests that these dikes were emplaced quite late in the igneous history of the complex, as the presence of serpentinite within these zones indicates that they were relatively cool (less than 500°C and probably between 100° and 300°C, Wenner and Taylor, 1973) when displacement was taking place along them. The mineralogy of the fault-zone dikes indicates that they belong to a late dike set which post-dates the dikes of the sheeted dike unit (see Section 4D).

Fault zones cutting gabbroic rocks are usually quite narrow (several cm to several m). Rocks within these zones are characterized by high degrees of alteration and intense jointing and veining. Slickenside lineationsoccur on some planar fault surfaces, but usually show highly variable orientations within individual fault zones.

Joints are common in all parts of the ophiolite. Their orientations are generally similar to those of neighboring faults. Joint density

Figure 35

Phacoidally cleaved serpentinite within a fault zone in layered ultramafic rocks (plate 2, location 6). Orange-weathering rocks at extreme left and right are uncleaved ultramafics. Discontinuous, tabular body near left margin of fault zone is a late rodingitized diabase dike.

tends to be highest near large faults and usually decreases rapidly away from them.

In most cases it is impossible to determine the age of individual faults cutting the ophiolite relative to the age of its emplacement. However, the rocks within one fault zone in area A and several others in area E show some indirect evidence of having formed prior to emplacement. These rocks are intensely altered breccias derived from ultramafic and/or mafic rocks (plate 2). The abundance of hydrous alteration phases and the presence of talc in some places within these zones indicates that they formed under relatively high temperature and P_{H_2O} conditions. Such conditions commonly occur in ocean-floor fault zones characterized by intense hydrothermal activity (Lowell, 1975; Wenner and Taylor, 1973), suggesting that these brecciated fault zones may represent relic ocean-floor features.

B. Folds

One of the most spectacular geologic features within the Betts Cove ophiolite is a large fold exposed in the hillside along the southern margin of area D (Figure 36). This structure has been interpreted by previous researchers as a fold formed by the rotation and collapse of a magma chamber lid during the formation of the ophiolite (Upadhyay, 1973; Dewey and Kidd, 1977). Considerable time was spent examining this fold during the course of field work in an effort to place some constraints on its origin.

Orientation data for folded dikes from area D (Figure 37) show the fold to be a slightly overturned, moderately northeast-plunging syncline which is somewhat conical in shape. A fold axis measurement obtained from an outcrop on the fold axial trace (plate 2) compares reasonably

Figure 36

Fold in area D (view northward from location 1, plate 2).

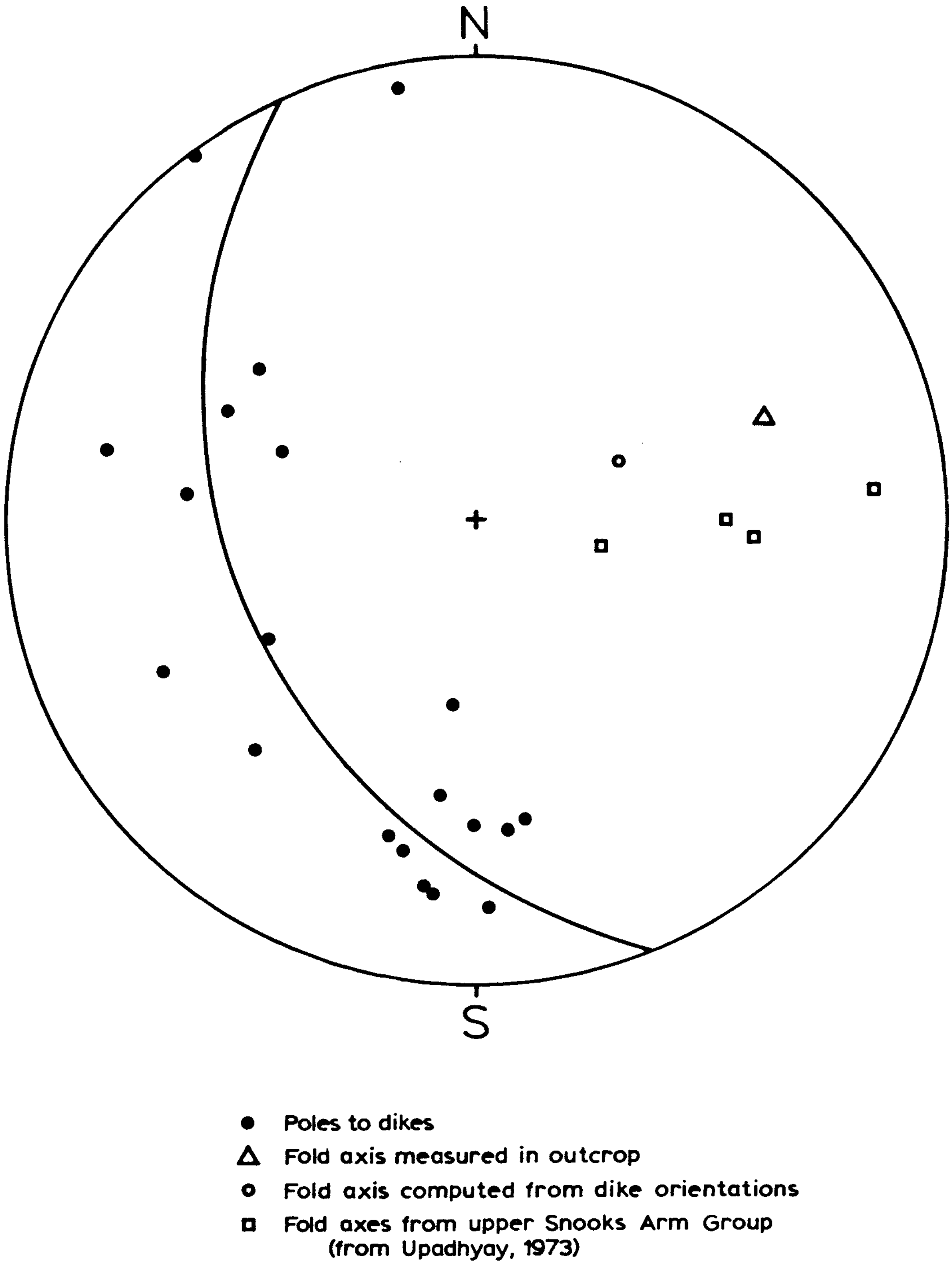


Figure 37

Orientation data for early diabase dikes and fold axes from the southwestern portion of area D.

well with the axis computed from dike orientations (Figure 37).

The hinge of this syncline is well-exposed in outcrops on the west side of area D. Diabase dikes in the hinge region are commonly slightly to strongly cleaved parallel with their margins. The axial trace of the fold is approximately parallel with igneous layering in the interlayered unit here, although no evidence of a penetrative layer-parallel foliation was observed in any rocks occurring near the hinge. Non-penetrative, layer-parallel joints are abundant, however. At the locality from which the measured fold axis oreintation shown on plate 2 was obtained, folded and cleaved dikes have been demonstrably offset along a small, layer-parallel (axial surface) fault (Figure 38). This suggests that deformation within the folded area may have been accomplished by a combination of ductile shearing and flexural slip (Donath, 1962) along diabase dikes, and displacement along non-penetrative, axial-planar brittle fractures in the gabbroic rocks, as described by Ramsay (1967, p. 403).

Map relationships depicted on plate 2 are quite complex within and adjacent to the fold hinge region of area D. A simple card deck model (Figure 39) was used here to determine the pre-folding geometry of lithologic contacts and igneous structures. This model demonstrates that the diabase dikes of the area were approximately perpendicular to igenous layering in the plutonic rocks prior to folding. Surfaces representing constant proportions of dikes cut progressively downward into the plutonic sequence as they are traced to the east. Similar irregularities in these surfaces (usually taken to be the base of the sheeted dike unit) have been reported from other ophiolites (i.e. Mings Bight, Kidd et al., 1978; Bay of Islands, Rosencrantz, 1980).

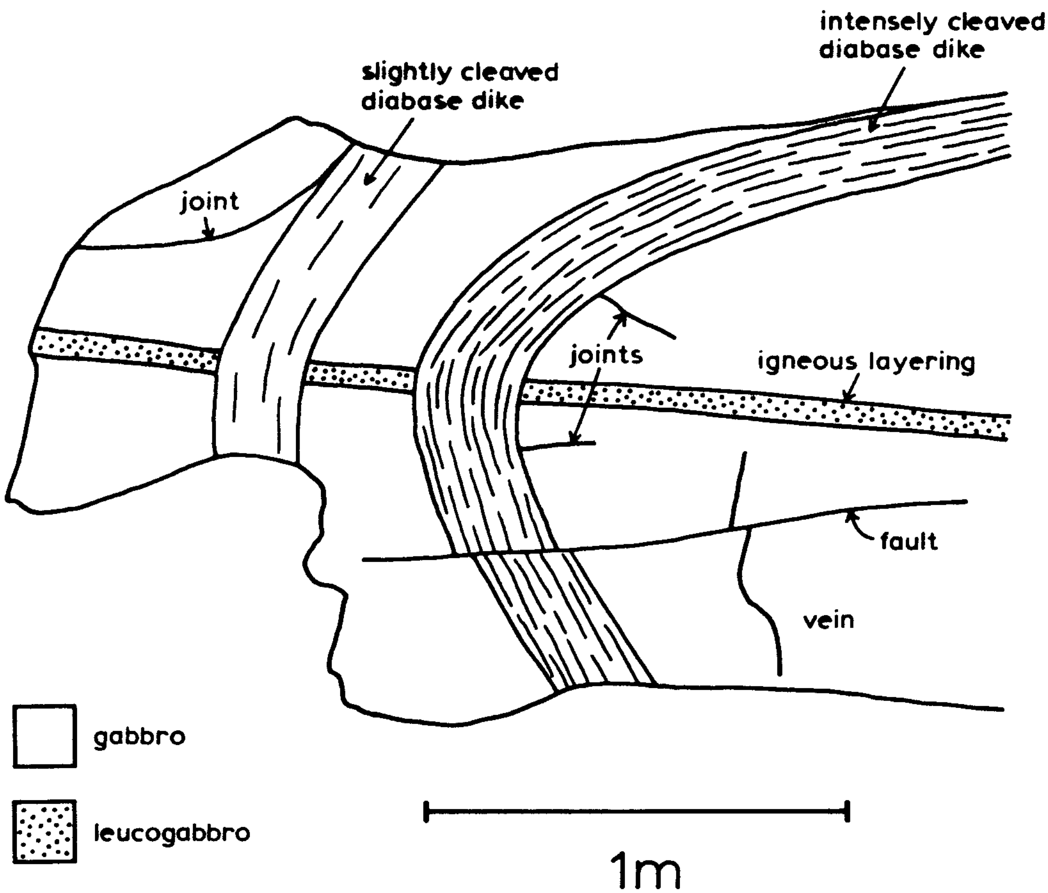
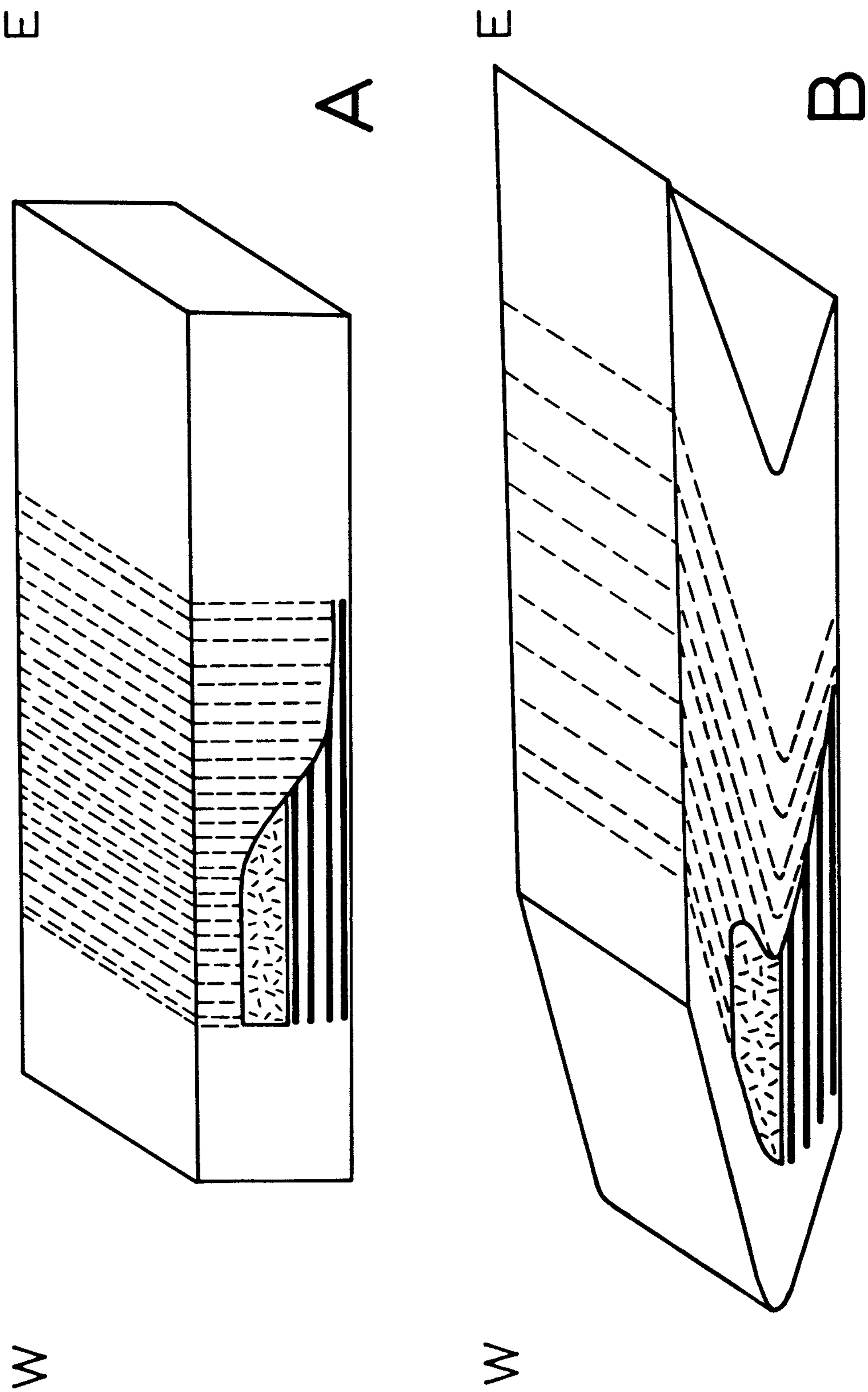


Figure 38

Sketch of an outcrop face in the southwestern portion of area D where the fold axis measurement shown on plate 2 was obtained (plate 2, location 7). Cleaved diabase dikes cut layering here, and are themselves cut by a small, layer-parallel fault.

Figure 39

Card-deck model illustrating the pre- and post-folding configurations of rocks in area D. A-original geometry, B-present geometry. Legend: Dashed lines-Plutonic rocks with <10% diabase dikes, stippled pattern-Homogeneous gabbroic rocks, heavy lines-Interlayered gabbroic and ultramafic rocks.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E
B
W

A gentle swing in the trend of dikes within the upper portion of the sheeted dike unit in area A suggests that a fold similar to that seen in area D may be partially developed here. The change in dike orientation is too small and the statistical scatter in dike orientations too large to prove this, however.

The orientation of the fold in area D is very similar to orientations obtained by Upadhyay (1973) from small parasitic folds within the sedimentary and volcanic rocks of the Snooks Arm Group (Figure 37). All of these folds have geometries and orientations which are nearly identical to those of the large syncline that folds the entire Snooks Arm Group. Because of the close similarity of these folds, it appears most reasonable to interpret the overturned syncline in area D as a parasitic fold related to larger-scale folding in the Snooks Arm Group, rather than a relic ocean-floor structure.

CHAPTER VI

METAMORPHISM

Low-grade metamorphism is a pervasive feature of the Betts Cove ophiolite. Alteration of original igneous phases as a result of this metamorphism is intense in most of the plutonic and hypabyssal rocks, and is responsible for obscuring many structural and igneous features. In addition, the chemical compositions of many of the ophiolitic rocks may have been rather strongly affected by metasomatism during the metamorphism. No detailed investigation of this metamorphism was attempted during the course of this project, but its general characterisitics and some resultant problems are discussed below.

Most of the plutonic and hypabyssal rocks of the ophiolite have undergone extensive green-schist facies metamorphism. Metamorphic phases produced as a result of this metamorphism include chrysotile, antigorite, lizardite, tremolite-actinolite, chlorite, Na-plagioclase, epidote, clinozoisite, sericite, quartz, calcite, and magnetite. The metamorphic grade is locally higher within the homogeneous gabbro unit, where the epidote-amphibolite facies assemblage blue-green hornblende + Na-plagioclase + epidote occurs in places.

Mapping within the Snooks Arm Group (Upadhyay, 1973; Jenner and Fryer, 1980) has demonstrated that metamorphic grade increases downward from zeolite facies in the uppermost portion of the sedimentary/volcanic sequence to predominantly green-schist facies in the ophiolitic rocks. Coish (1977a, b) has shown that the grade and intensity of greenschist-facies metamorphism increases progressively downward within the ophiolite itself. He interpreted this metamorphism as being of ocean-floor origin, based on the following creteria:

1) Metamorphic grade and intensity increase downward in the complex with little or no evidence of tectonic deformation.
2) Geothermal gradients of greater than 300^{o}C/km are indicated by the presence of actinolite within 1 km of the top of the complex.
3) Petrographic and chemical data suggest that the metamorphism involved hydrothermal alteration and metasomatism.

These criteria are all consistent with present knowledge of ocean-floor metamorphism derived from theoretical and experimental modeling (Hart, 1973; Lister, 1974; Hajash, 1975; Wolery and Sleep, 1976), and from marine studies (Melson and Van Andel, 1966; Miyashiro, et al., 1971, 1979; Aumento and Loubat, 1971; Bonatti, et al., 1975). In light of these similarities, it appears most reasonable to interpret much, if not all, of the metamorphism affecting the Betts Cove ophiolite as being of ocean-floor origin. Studies of metamorphism in other ophiolites (Spooner and Fyfe, 1973; Gass and Smewing, 1973; Stern et al., 1976; Elthon and Stern, 1978; Abbotts, 1979) have indicated that ocean-floor metamorphism is a pervasive and important feature of ophiolite complexes.

The effects metamorphism has had on the Betts Cove ophiolite are many and varied, but the one which is perhaps most significant with regard to recent studies is chemical migration. A number of researchers have used geochemical data to make inferences concerning the igneous and tectonic history of the Snooks Arm Group. Coish (1977a) and Coish and Church (1979) have used trace and rare-earth element data to show that the magma which produced the hypabyssal and volcanic portions of the ophiolite was apparently quite depleted in incompatible trace and rare-earth elements, and was the product of partial melting of "severely depleted" mantle material. Major element analyses of some altered Betts Cove dikes and volcanics (Upadhyay, 1976, 1978)has shown them to have komatiitic (high-Mg) compositions. The results of a geochemical study of volcanic rocks from the upper portion of the Snooks Arm Group has led Jenner and Fryer (1980) to suggest that they were formed in oceanic island or marginal basin setting.

Variable mobility of major elements (Smith, 1968), trace elements (Humphris and Thompson, 1978), and rare-earth elements (Hellman et al., 1979) has been demonstrated during metamorphism of mafic rocks. Coish (1977b) has shown that most major elements and some trace elements (Ba, Rb, Sr, Cu) were mobilized to varying extents during the metamorphism of Betts Cove pillow lavas. The presence of massive sulfide deposits within the ophiolite (Upadhyay and Strong, 1973) suggests that extensive leaching and migration of Cu, and possibly other trace elements, has occurred.

This evidence for chemical migration during metamorphism in the Betts Cove ophiolite casts some doubt on the validity of previous interpretations based on geochemical data. The studies of Coish (1977a) and Coish and Church (1979) make use of some trace elements (Ti, Zr, Y, Cr, Ni) shown to be relatively immobile by Coish (1977b), but also rely heavily on rare-earth elements, the mobility of which has not been determined in Betts Cove. Upadhyay's (1976, 1978) work on altered, highly magnesian dikes and volcanics must be interpreted carefully in light of evidence that the MgO content of these rocks increases drastically with increasing alteration (Coish, 1977b). Jenner and Fryer (1980) have apparently not considered chemical migration at all during their work.

Many interpretations based on the results of these studies can be substantiated by other, non-chemical methods. The abundance of evidence for extensive metasomatism and chemical migration in the Betts Cove ophiolite indicates, however, that petrologic and tectonic inferences based solely upon geochemical data should be interpreted with caution.

CHAPTER VII

SUMMARY AND CONCLUSIONS

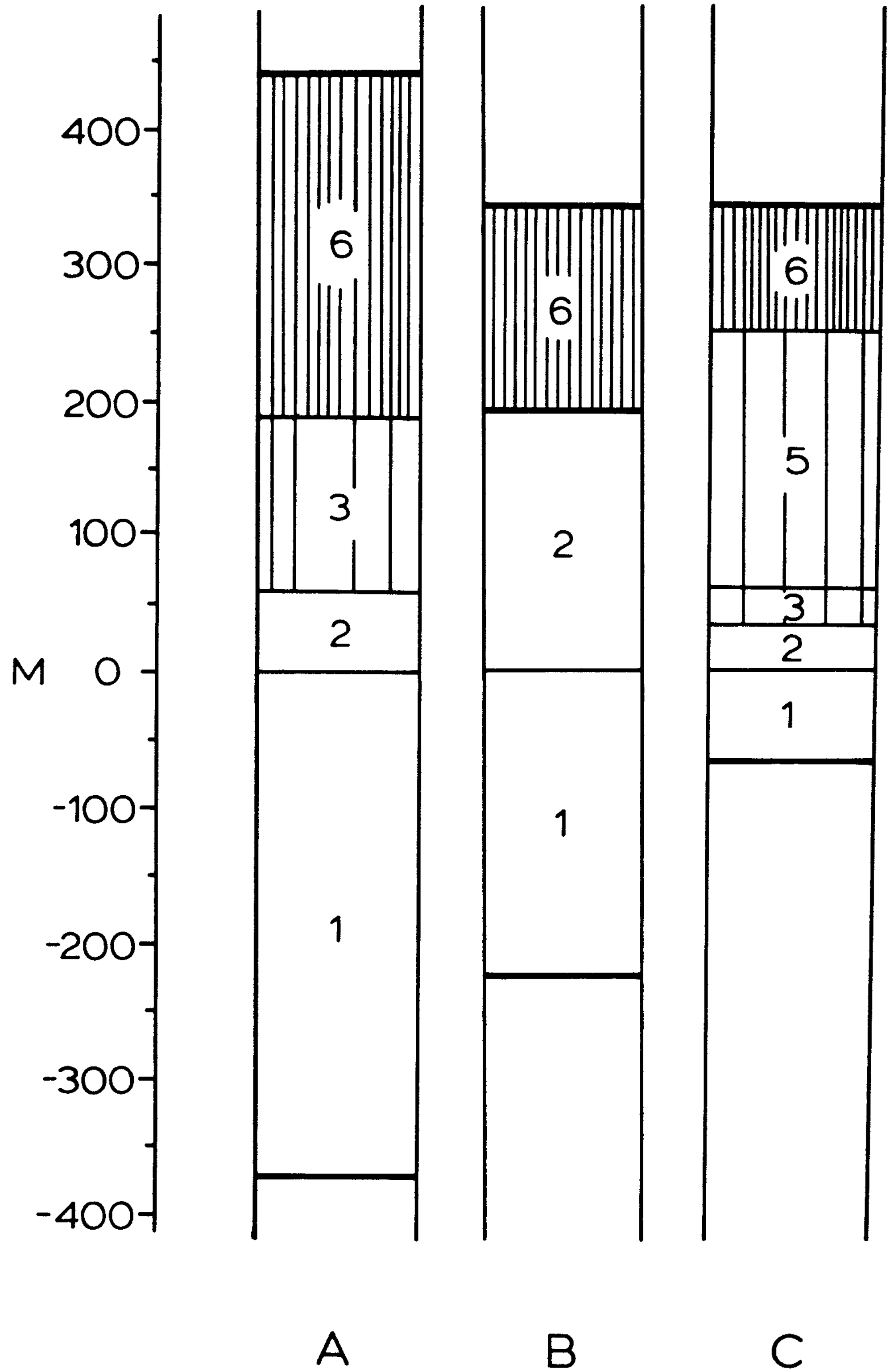
Detailed mapping in the plutonic and hypabyssal portion of the Betts Cove ophiolite accomplished during this study shows it to consist of the following lithologic units (from the exposed base upwards):

1) A sequence of layered ultramafic rocks, which have a minumum thickness of 375 m. These consist predominantly of altered harzburgite, lherzolite, pyroxenite, and dunite, with minor gabbroic rocks. Most of these are intensely serpentinized, but show excellent preservation of igneous textures and mesoscopic structures. They are characterized by centimeter- to meter-scale igneous layering and isolated examples of other igneous features such as trough and channel structures, igneous foliations and lineations, etc. The upper portion of this sequence is extensively cut by intrusive, pegmatitic clinopyroxenite, which shows evidence of having been remobilized from pyroxene-rich layers. Gabbroic rocks appear in small quantities near the top as thin layers, dikes, sills, veins, and more irregular, small intrusive bodies.

2) Interlayered gabbroic and ultramafic rocks, which range from 65 to 190 m or more in thickness and are in gradational contact with the underlying ultramafic rocks. These consist of variably altered gabbro, gabbronorite, and ultramafic rocks similar to those comprising the underlying unit. These rocks are well-layered and exhibit many of the same igneous features observed in the layered ultramafic rocks. Lower portions of this unit are extensively cut by intrusive gabbro and clinopyroxenite.

Figure 40

Lithologic sections from areas A, B, and C. Locations of sections used to determine unit thicknesses are shown on plate 3. Legend: 6-Sheeted diabase dikes (>95% dikes), 5-Homogeneous gabbroic rocks (>10% dikes), 3-Interlayered gabbroic and ultramafic rocks (>10% dikes), 2-Interlayered gabbroic and ultramafic rocks (<10% dikes), 1-Layered ultramafic rocks (<10% dikes). Light lines mark lithologic contacts, heavy lines are faults.


400
300
200
100
M 0
-100
-200
-300
-400
6
3
2
1
6
2
1
6
5
3
2
1
A
B
C

3) Homogeneous gabbroic rocks, which gradationally overlie the interlayered sequence and have a maximum thickness of 195 m, but may be locally absent. These consist almost entirely of variably altered gabbro. Well-developed igneous layering is generally absent from most of this unit, which is characterized by poorly developed, inconsistently oriented layering and irregular, diffuse patches of pegmatitic gabbro. Quartz-bearing metabasites occur locally in areas of extensive metamorphism and lateration.

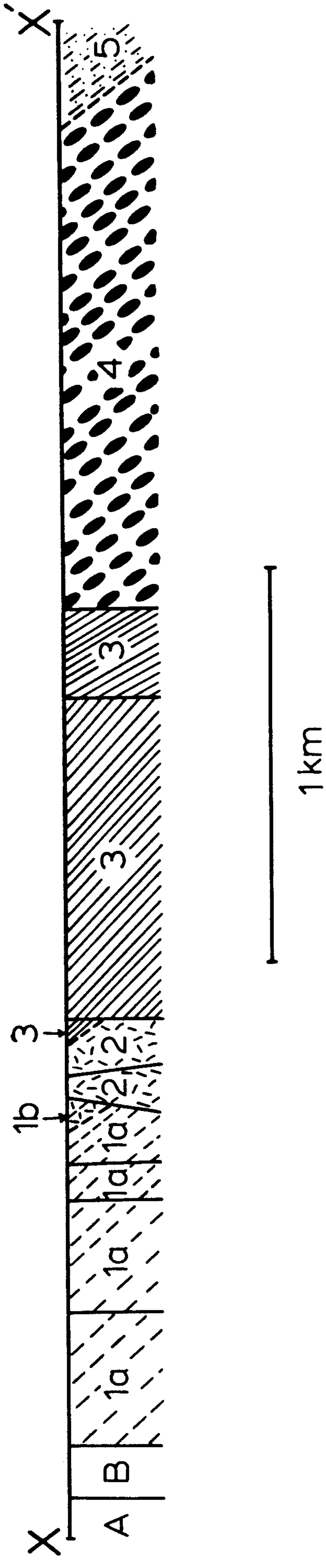
4) Sheeted diabase dikes, which are greater than 260 m thick. These are variably altered and contain less than 5% coarse-grained screens consisting of gabbro and lesser pyroxenite. Dikes belonging to the same generation as those comprising the sheeted dike unit cut all of the units of the ophiolite, and generally increase in abundance upward. The dikes of the sheeted dike unit cut homogeneous gabbroic rocks of the underlying unit in most places, although they are locally intruded by the gabbro.

Representative lithologic sections summarizing the plutonic and hypabyssal sequences of areas A, B, and C appear in Figure 40. Data from areas D and E are not shown, as structural complexities in these areas (discussed in previous chapters) make any reasonably accurate determinations of unit thicknesses in these areas impossible.

Structural complexities disrupt portions of the ophiolite stratigraphy in nearly all parts of the complex, making it impossible to construct cross-sections through completely undismembered portions of the entire ophiolite sequence. Figure 41 illustrates a generalized

Figure 41

Cross-section through the Betts Cove ophiolite. Line of section is indicated on plate 1. Legend: 5-Sedimentary rocks, 4-Volcanic rocks, 3-Sheeted diabase dikes, 2-Homogeneous gabbroic rocks, 1b-Interlayered gabbroic and ultramafic rocks, 1a-Layered ultramafic rocks, N-Undifferentiated ophiolitic rocks (Nippers Harbour Group), P-Quartz-feldspar porphyry. Lithologic contacts appear dashed, faulted contacts are solid lines.


X'
5
4
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3
1 km
3
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2
1a
1a
1a
1a
1a
B
A
X

cross-section drawn through the complex along the same line used by Dewey and Bird (1971) to construct a similar section. Offsets on both major and minor faults along this line have divided the section into a number of structural blocks. Exact correlations between some of these blocks are impossible, and as a consequence the line cannot be used to reconstruct a complete section through the complex. This can only be done by piecing together partial, internally intact sections from different localities within the ophiolite.

It is now generally accepted that ophiolite complexes preserved in mountain belts are remnants of old oceanic crust and mantle (Gass, 1968; Moores and Vine, 1971; Dewey and Bird, 1971; Church and Stevens, 1971; Conference Participants, 1972). Most ophiolites, where structurally intact, have been shown to be characterized by the following sequence of rock types (from top to base):

1) Volcanic rocks (generally basaltic)
2) Hypabyssal mafic intrusive rocks (usually sheeted diabase dikes)
3) Mafic and ultramafic plutonic rocks
4) Ultramafic tectonites (mostly harzburgite)

The Betts Cove ophiolite contains a partial sampling of this sequence (the ultramafic tectonites are apparently not exposed), but despite the fact that significant differences in ophiolite unit thicknesses have been shown to exist it appears to contain an anomalously thin plutonic section relative to most ophiolites (Figure 42). One of the major purposes of this study was to determine if the thin plutonic section was real or an artifact of previous generalized mapping and undetected faulting. The results of the study show that the small thickness of

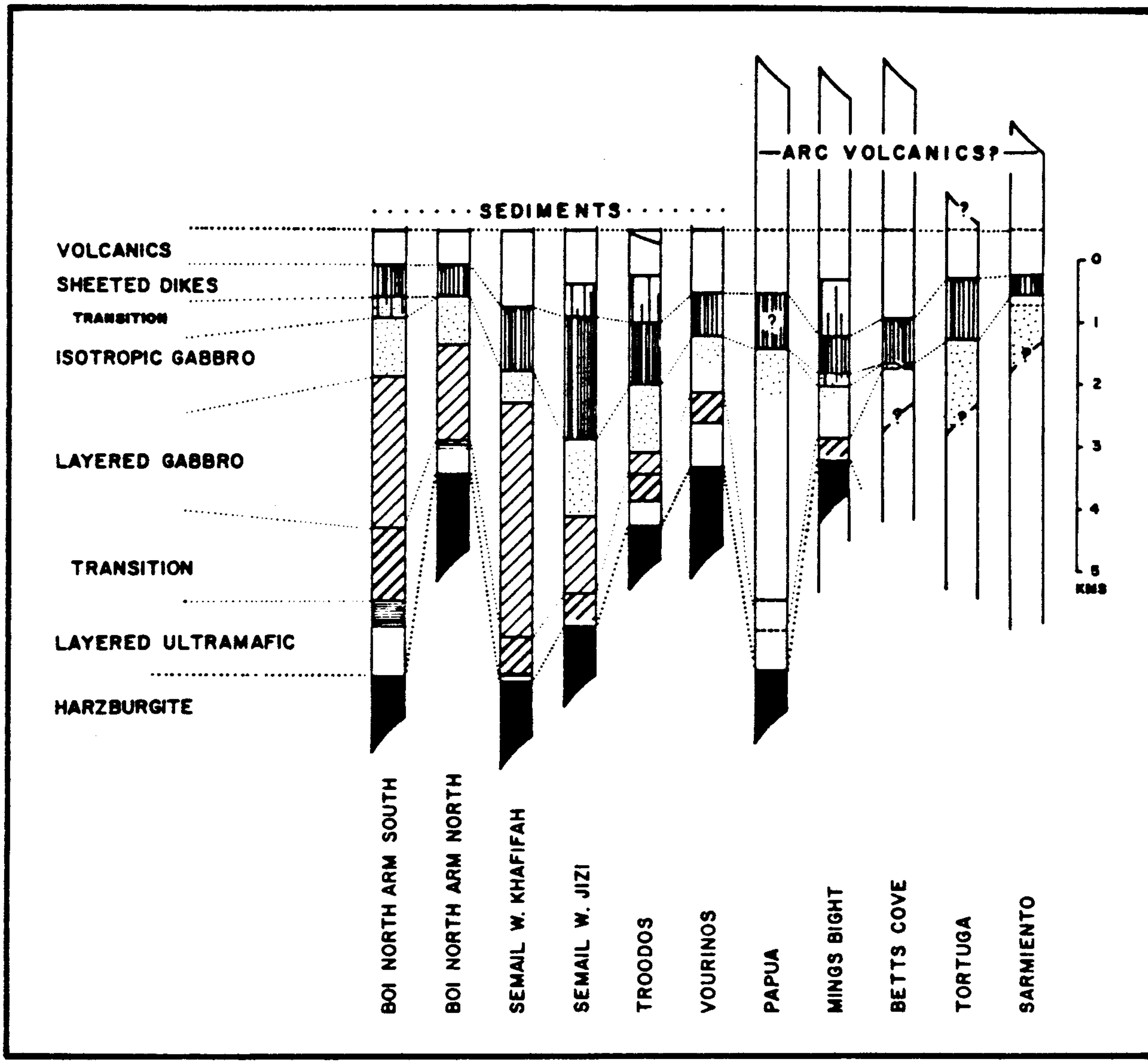


Figure 42

Correlation of unit thicknesses between various ophiolites (from Rosencrantz, 1980).

the plutonic section is a primary property of the ophiolite, despite the abundance of faulted contacts that do not appear on the previous maps of Upadhyay et al. (1971), Upadhyay (1973), and Riccio (1972). The gabbroic portion of the plutonic section is particularly thin - in some places it has been demonstrated to be less than 100 m thick, while the gabbros of the nearby Bay of Islands ophiolite are nearly everywhere in excess of 3 km thick, for example.

It is difficult to decide in many cases whether variations of this types are the result of fundamental differences in the processes responsible for the formation of individual ophiolites, or simply small variations in a process common to the formation of all ophiolite compleses. General models for the formation of oceanic crust based on compilations of data from a number of ophiolite complexes (i.e. Dewey and Kidd, 1977) do not appear to explain all of the characteristics and features of some ophiolites, suggesting that different and perhaps unrelated processes are dominant in the formation of different ophiolites. In formulating the model for the formation of the Betts Cove ophiolite discussed in this chapter, it was decided to use only those constraints which could be demonstrated to occur in this complex wherever possible. This model should therefore not be taken as a general model for the formation of oceanic crust, but rather one which best explains the general characteristics of the Betts Cove ophiolite and its formation.

A number of more or less detailed models for the formation of oceanic crust based on ophiolite data have been proposed in recent years (Moores and Vine, 1971; Greenbaum, 1972; Dewey and Kidd, 1977; Hopson and Pallister, 1980). Models suggested for the Betts Cove ophiolite (Riccio, 1972; Upadhyay, 1973) have, however, been extremely general to date.

Generation of an accretion model based on Betts Cove data is difficult for a number of reasons. Most of the complex is cut by faults and partially dismembered. Individual fault-bounded sections rarely exceed 1 km in along-strike width. The nature of movement and offset along these faults is poorly known, and fairly large variations in the stratigraphy and unit thicknesses of adjacent structural blocks make correlations difficult. Late folding has affected parts of the complex, hindering comparisons of orientation data collected from different areas. In addition, intense, low-grade metamorphism and alteration have obscured many aspects of the mineralogy and chemistry.

Despite these problems, data from the plutonic and hypabyssal portion of the complex, when combined with structural, lithologic, and chemical data from other studies, provides enough constraints to allow the production of a reasonably unique model. In addition to the general lithologic and structural characteristics of the ophiolite summarized in the beginning of this chapter, the following observations made during this study provide significant constraints for modelling of Betts Cove accretion processes:

1) The plutonic and hypabyssal portion of the ophiolite is a continuous, uninterrupted igneous sequence, with all parts generated contemporaneously. No evidence was found for any "important discordance" or "major discontinuity" between the ultramafic and gabbroic rocks, as suggested by Riccio (1972), Church and Riccio (1974), and Church (1977).
2) Igneous layering occurring within the interlayered and layered ultramafic units is generally at low to moderate

angles to adjacent unit contacts.

3) Diabase dikes related to those of the sheeted dike unit (early dikes) are approximately perpendicular to unit contacts, except where affected by late folding.

4) Early diabase dikes locally cut rocks of the interlayered and layered ultramafic units.

5) Screens of plagioclase-bearing pyroxenite and melagabbro occur locally in the lower portion of the sheeted dike unit even where the unit overlies considerable thicknesses of relatively leucocratic homogeneous gabbroic rocks.

6) Dikes of the sheeted complex commonly cut homogeneous gabbroic rocks at the base of the complex, but can be shown to be underplated by the gabbro in places.

7) Homogeneous gabbroic rocks are locally very thin or absent; sheeted dikes grade downward into and <u>cut</u> layered rocks in these areas.

8) No evidence exists within the complex for penetrative, high temperature deformation of the plutonic/hypabyssal sequence.

As discussed in previous sections, the plutonic and hypabyssal portion of the Betts Cove ophiolite has been moderately to intensely altered as a result of pervasive ocean-floor metamorphism. Metasomatism accompanying this metamorphism has mobilized many of the major and trace elements in the ophiolite (Coish, 1977b). For this reason it was decided to base inferences relating to the formation of the ophiolite presented in this chapter on geometric, lithologic, and petrographic constraints wherever possible.

Recent studies of the geochemistry of the Betts Cove ophiolite, however, show promise of providing useful information on the igneous processes responsible for the formation of the complex. By using data for minor and trace elements demonstrated by Coish (1977b) to have been relatively immobile during metamorphism, Coish (1977a) and Coish and Church (1979) have shown that the volcanic rocks comprising the top of the ophiolite sequence at Betts Cove are divisible into three groups. The lower- and intermediate-level volcanics, as well as most of the sheeted dikes, are extremely depleted in TiO_2 (less than 0.5%) and other incompatible trace and rare-earth elements. They are also characterized by high Ni and Cr contents relative to "normal" mid-ocean ridge tholeiites. Upper level lavas are more enriched in incompatible elements and have compositions more closely approximating those of modern ocean-floor basalts.

The chemistry of the lower volcanic rocks suggests that they were produced by fractionation of a partial melt derived from a severely depleted mantle source (Sun and Nesbitt, 1978; Coish and Church, 1979). Coish and Church (1979) have found picritic dikes within the sheeted dike unit which have compositions similar to those predicted for primitive melts derived by this process. Similar picritic dikes from the Tortuga ophiolite have been suggested as possible primitive melts by Elthon (1979).

The mineralogy of the plutonic rocks of the ophiolite provides an independent check on this hypothesis. Recent studies (Riccio, 1977; Church and Riccio, 1977; Serri, 1980) have shown that the compositions of primitive melts from which ophiolites (and oceanic crust) have been derived is reflected in the mineralogy of their plutonic rocks. Ophiolites with high-Ti volcanic and hypabyssal rocks (i.e. the Bay of Islands complex) apparently derived from partial melting of a relatively undepleted mantle have plutonic sequences characterized by rocks rich in olivine, clinopyroxene, and plagioclase, with rare orthopyroxene. In constrast, ophiolites with low-Ti extrusive and hypabyssal sections believed to have been derived from depleted mantle sources are characterized by orthopyroxene-rich plutonic rocks. The abundance of orthopyroxene in Betts Cove plutonic rocks therefore lends additional support to the arguments of Coish and Church (1979).

A speculative model for the formation of the Betts Cove ophiolite based on the constraints discussed in this chapter is presented in Figure 43. This model assumes that the plutonic and hypabyssal portion of the ophiolite formed by sea-floor spreading in a single, steady-state magma chamber from a picritic primitive melt. It is similar in many respects to magma chamber models proposed for the Troodos (Greenbaum, 1972) and Semail (Hopson and Pallister, 1980) ophiolites. Processes related to the formation of depleted mantle tectonites (harzburgite and lhercolite) occurring in many ophiolites are not discussed, as these rocks have not been proven to occur in the Betts Cove ophiolite.

The geometry of the magma chamber shown in Figure 4 was derived solely from lithologic and structural data collected from the plutonic and hypabyssal portion of the ophiolite. The low to moderate angle between igneous layering and unit contacts observed in the field (β in Figure 43) defines the dip of the magma chamber floor. Since β values across the map area range from less than 10° to a maximum of about 35°, an intermediate (and in some respects arbitrary) value of 20° was used. Dewey and Kidd (1977) have argued that dip angles greater than 5° should result in instability and downslope movement of crystals accumulating

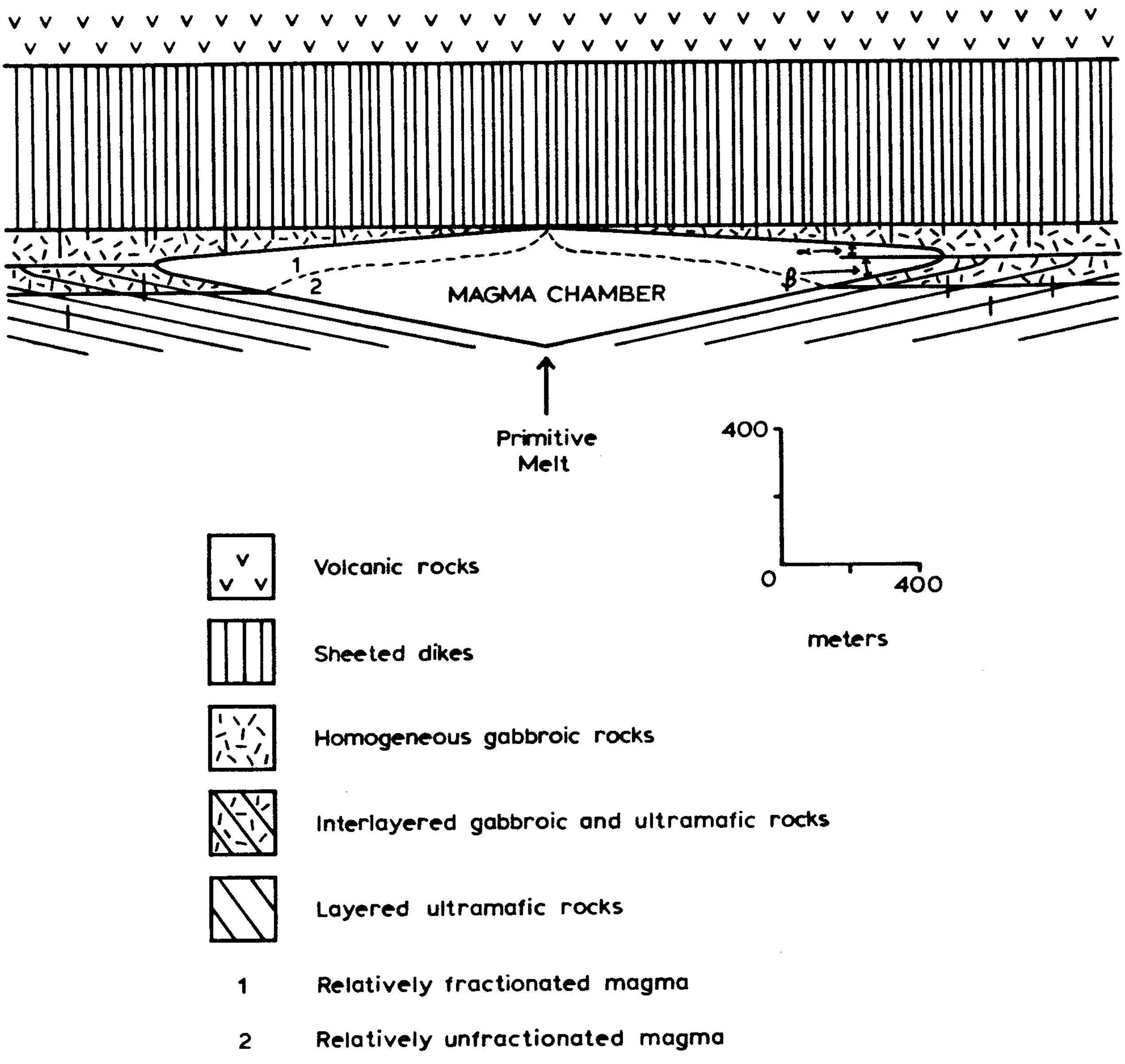


Figure 43

Proposed model for the formation of the Betts Cove ophiolite.

along the floor, and could not be dynamically maintained. Casey (1980), and Casey and Karson (1981) have demonstrated, however, that steeply dipping, undisturbed igneous layering seen in the Bay of Islands ophiolite was formed by in situ crystallization along originally steep surfaces.

The half-width of the proposed magma chamber is a function of β and the thickness of the layered sequence. This thickness was chosen to be 550 m. The actual thickness of the layered sequence is not known, however, and may actually be greater than this value. Greater thicknesses would result in a larger magma chamber having the same geometry. Similarly, the dip of the magma chamber roof (α in Figure 43) is proportional to the thickness of homogeneous gabbro present, chosen to be 250 m in this case. The absence of homogeneous gabbroic rocks in places may be a result of local α values of zero (i.e. a flat roof). The chosen values of α, β, and total magma chamber thickness define a shallow, sill-like magma chamber having a width to height ratio of 6 to 1 or greater. The lid of this chamber would probably have to float on the underlying magma (Rosencrantz, 1980) for support.

A magma chamber with the proposed geometry residing at shallow crustal levels would presumably be characterized by a steep vertical thermal gradient. If primitive melt entered the chamber along a narrow axial welt, as suggested by Dewey and Kidd (1977), a strong lateral thermal zonation of the chamber would also be expected. The combined effect of these thermal variations would be to crystallize fairly primitive melt (producing layered ultramafic rocks) along the bottom of the magma chamber near the axis, and more highly fractionated melt (producing interlayered rocks and homogeneous gabbro) along the margins and roof.

The small height (less than 1 km) of the proposed magma chamber might allow hot, upward-convecting primitive melt directly over the chamber axis to (intermittently?) reach the base of the sheeted dike unit, where it would presumably feed the hypabyssal/volcanic carapace of the ophiolite. Picritic dikes produced by this mechanism would be underplated and intruded by pyroxene-rich, primitive plutonic rocks near the axis, producing pyroxenite screens at the base of the sheeted dike unit. Continued spreading would result in the underplating of this entire sequence by homogeneous gabbroic rocks. Subsequent dike injection would produce dikes cutting the homogeneous gabbroic rocks. These would tap increasingly fractionated melt toward the margins of the magma chamber.

The origin of fine-grained mafic dikes cutting the layered rocks of the ophiolite is not easily explained by this model. These dikes may have been intruded downward into the layered rocks, but this seems mechanically and thermally unfeasible. The fact that these dikes do not cut the entire exposed thickness of layered rocks strongly suggests, however, that they were derived from adjacent or overlying levels. It is most likely that the dikes were derived locally from basaltic melt trapped interstitially or in small pockets in the layered rocks after their deposition along the margins of the magma chamber.

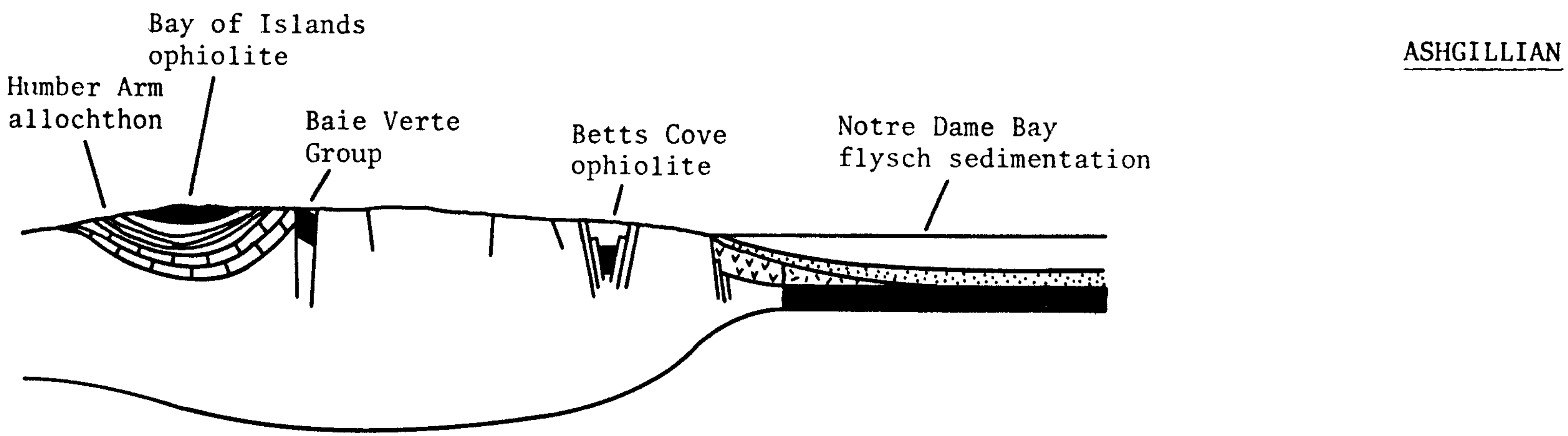
It has been proposed by a number of researchers that the Betts Cove ophiolite represents oceanic crust formed in a marginal basin setting (i.e. Church and Stevens, 1971; Dewey and Bird, 1971; Upadhyay et al., 1971), based largely on regional relationships summarized in Chapter II. The distribution of basaltic rock types in modern tectonic environments provides further support for a marginal basin origin of the ophiolite.

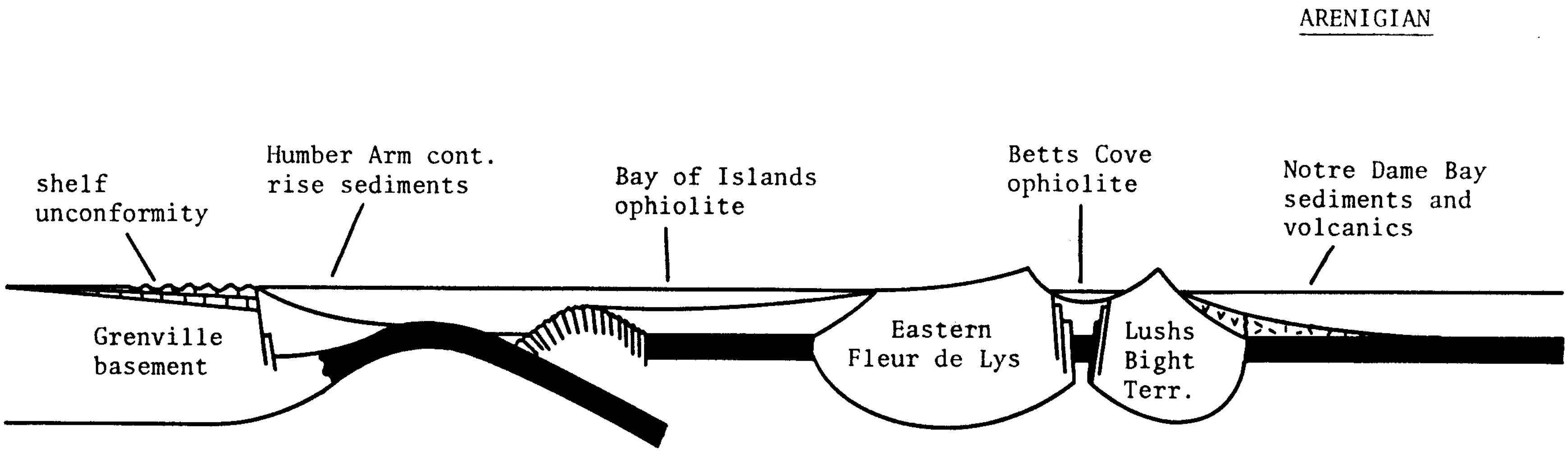
Boninites and low-Ti basalts have been shown to occur fairly exclusively in island arc and marginal basin settings (Pearce, 1975; Sun and Nesbitt, 1978). In addition, experimental petrology has shown that these rock types are most likely produced by high degrees of high-temperature, water-saturated partial melting of depleted mantle material at moderate pressures (Green, 1976). Such conditions have been suggested to occur over subducting slabs during the early phases of back-arc spreading (Serri, 1980).

Schematic sections based on these findings which illustrate a possible tectonic setting for the formation of the Betts Cove ophiolite (after Nelson and Casey, 1979), and its present structural setting appear in Figure 44.

Figure 44

Proposed tectonic setting for the formation and evolution of the Betts Cove ophiolite (after Nelson and Casey, 1979).


ASHGILLIAN
Humber Arm
allochthon
Bay of Islands
ophiolite
Baie Verte
Group
Betts Cove
ophiolite
Notre Dame Bay
flysch sedimentation


ARENIGIAN
shelf
unconformity
Grenville
basement
Humber Arm cont.
rise sediments
Bay of Islands
ophiolite
Eastern
Fleur de Lys
Betts Cove
ophiolite
Lushs
Bight
Terr.
Notre Dame Bay
sediments and
volcanics

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