The Structural Geology of the Tectonized Ultramafic Suite of the Table Mountain Massif, Bay of Islands Complex, Newfoundland

Abstract of
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

Robert Whitney Blake

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ABSTRACT

Table Mountain is the northernmost massif in the Bay of Islands Ophiolite. It represents a continuous, approximately 7 kilometer thick, section of residual harzburgite tectonites capped by a nearly flat-lying assemblage of deformed and undeformed cumulate rocks. The notable mesoscopic structural features of the massif include a zone of penetrative deformation extending upsection from the tectonized harzburgites approximately 500 meters into the dunites and basal cumulates. The orientation of the foliation and associated lineations as well as the inferred shear sense within the zone is consistent with that affecting the harzburgites. Highly deformed dunite lenses which range in thickness up to 300 meters and up to 5 kilometers in lateral extent lie beneath the plagioclase-bearing cumulates. They have a gradational contact with the harzburgites. Throughout the harzburgite section compositional layering, defined by variations in enstatite concentration, is parallel or nearly parallel to the S_1 foliation. The layering may either have limited lateral extent (associated with transposed intrusives) or it occurs in clusters of layers traceable as a group for several kilometers. The inclination of both the foliation and the layering relative to the essentially flat-lying contact between the cumulate and residual suites becomes progressively more shallow at deeper levels within the harzburgite. Petrographic examination of the massif indicates the presence of clinopyroxene and altered plagioclase (now hydrogarnet and sericite) in the upper 50 to 200 meters of harzburgite adjacent to the

dunite lenses. Trace amounts of subhedral clinopyroxene occur throughout the harzburgite, typically associated with polycrystalline enstatite clots. Petrofabric analyses of olivine fabrics of samples from the harzburgite section indicate that the [100] maxima strengthen with increasing depth from the cumulate carapace. Fabric assymmetries relative to the trace of the foliation and spinel lineation indicate a dominantly sinistral shear sense. This concurs with the consistently oriented fold vergence data. A model of a spreading ridge system, modified after Dewey and Kidd (1977) and Casey (1980), is adapted to explain the "herringbone" relationship between the compositional layering of the undeformed cumulates and that of the S_1 foliation. This foliation is here proposed to dip away from the parental ridge axis.

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The thesis for the master's degree submitted by

Robert Whitney Blake

under the title

The Structural Geology of the Tectonized Ultramafic Suite of the Table Mountain Massif, Bay of Islands Complex, Newfoundland

has been read by the undersigned. It is hereby recommended for acceptance by the Faculty with credit to the amount of

___________________ semester hours.

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Recommendation accepted by the Dean of Graduate Studies for the Graduate Academic Council.

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I am indebted to Bill Kidd not only for introducing me to Table Mountain but especially for his continued advice and friendship throughout my stay at Albany. My first field season would never have passed as smoothly as it did without the advice of Newfoundland veterans Bruce Idleman and Dave Rowley. Roger Powers accompanied me into the field, surviving a summer of wind, rain, black flies and talus admirably. The open hospitality of the people of Trout River made both my trips there unforgettable. I would especially like to mention Sam and Willy Parsons who provided many a Sunday dinner, beers and companionship when I wasn't "out prospecting".

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Most importantly, I am indebted to my wife, Martha, whose love, unending patience and assistance kept me going and enabled me to complete this thesis.

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The northern and eastern faces of Table Mountain as viewed from the South Arm of Bonne Bay.

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To Martha and My Parents

CHAPTER I

INTRODUCTION

To date, ophiolites are the most accessible source of information concerning the lithologic and structural constitution of the intrusive, plutonic and residual elements of oceanic crust. The Bay of Islands Complex (Stevens, 1970) is a remarkably complete and undeformed ophiolitic nappe.

Previous Work and Purpose

The initial work on the igneous complex of the Bay of Islands massifs was undertaken by Snelgrove (1934), Ingerson (1935), Cooper (1936) and Buddington and Hess (1937). Debate largely centered around the interpretation of the individual massifs as separate laccoliths (Ingerson, 1935), or, in the case of Table and North Arm Mountains, a single lopolith offset by a fault system along Trout River Ponds (Buddington and Hess, 1937). Cooper (1936) formed a similar conclusion for the Blow Me Down and Lewis Hills massifs. These workers also recognized and discussed the compositional layering within the ultramafic and gabbroic sections.

The first comprehensive study of the entire complex was completed by Smith (1958). In a Geological Survey of Canada Memoir, he published a map of the Complex at the scale of 1:126,720. Smith concluded that the mafic and ultramafic assemblages formed as the result of differentiation of basaltic magma which intruded a country rock consisting of mafic volcanics, diabase, and the Humber Arm clastic sedimentary rocks. He did recognize numerous structures indicative of high temperature ductile deformation. This led him to propose that much of the Complex was intruded as a crystal mush.

The advent of plate tectonics in the late 1960's led to recognition of ophiolite complexes as allochthonous slices of oceanic crust and upper mantle (e.g. Moores and Vine, 1971). Stevens (1970) and Dewey and Bird (1971) were first to interpret the Bay of Islands Complex as an ophiolitic nappe. Much work has since concentrated on the structural succession of the various blocks within the complex (Williams and Malpas, 1972; Williams, 1975; Casey and Kidd, 1981), the nature of the volcanic assemblages (Williams, 1973; Rosencrantz, 1980), and also on the plutonic suite (Malpas, 1977; Dewey and Kidd, 1977; Casey, 1980). O'Connell (1979) mapped the plutonic suite exposed on Table Mountain on a scale of 1:15,000. As a result of these studies, the heterogeneity of oceanic crust formed along one ridge system was inferred (Casey et al, 1981)

The residual nature of the tectonized harzburgites exposed on the massifs has been clearly demonstrated by the geochemical and petrological analyses of Strong and Malpas (1975), Mercier (1976 a, b) and Girardeau and Nicolas (1981). Petrofabric studies have also been undertaken on all the massifs except Lewis Hills (Mercier, 1976; Christensen and Salisbury, 1979; Girardeau, 1979; Girardeau and Nicolas, 1981). This work has concentrated upon olivine fabrics, and spinel and tabular enstatite lineations, within the tectonites.

Perhaps the most distinctive feature of the Bay of Islands Complex is the preservation of an oceanic fracture zone (Karson, 1977; Karson and Dewey, 1978). Coupling this observation with the remarkably intact, complete section and relatively undeformed nature of the entire complex gives researchers a unique opportunity to examine the structures developed along oceanic ridge/transform intersections. A perplexing diversity of models have been proposed for the ridge system which generated this ophiolite (Church and Riccio, 1975; Malpas, 1977; Dewey and Kidd, 1977; Casey, 1980; Girardeau and Nicolas, 1981). In most aspects, these models are incompatible with one another, and reconstructed orientations of the paleo-ridge relative to the present orientation of the massif differ by as much as 90 degrees (e.g. Karson and Dewey, 1978 versus Girardeau and Nicolas, 1981).

This thesis reports on detailed structural traverses through the tectonized units exposed along the northern and southern flanks of Table Mountain. Much attention was given to the nature of the uppermost residual tectonites and to the variations in structure and fabric at progressively lower levels within the tectonized peridotites. The primary objective of this work is to attempt to establish a geometrical relationship between the structural elements of the tectonized cumulate and residual units and the spreading ridge along which the ophiolite was generated and, perhaps, a ridge transform intersection nearby.

The research reported here is part of a comprehensive study of the entire Bay of Islands Complex initiated by John Dewey and W.S.F. Kidd.

Location and Access

The Bay of Islands Complex is composed of a series of four large massifs and other smaller blocks covering an area approximately 100 km long and 25 km wide along the western coast of Newfoundland (Figure I-1). Table Mountain is the northernmost massif, although a block of the Coastal Complex wraps around its western and northern faces forming the southwest peninsula of Bonne Bay and the Gulf of St. Lawrence. The section of Route 44 running West from the town of Woody Point to the coastal fishing village of Trout River approximately bounds the northern and northwestern margins of Table Mountain. The massif lies within the southern domain of Gros Morne National Park.

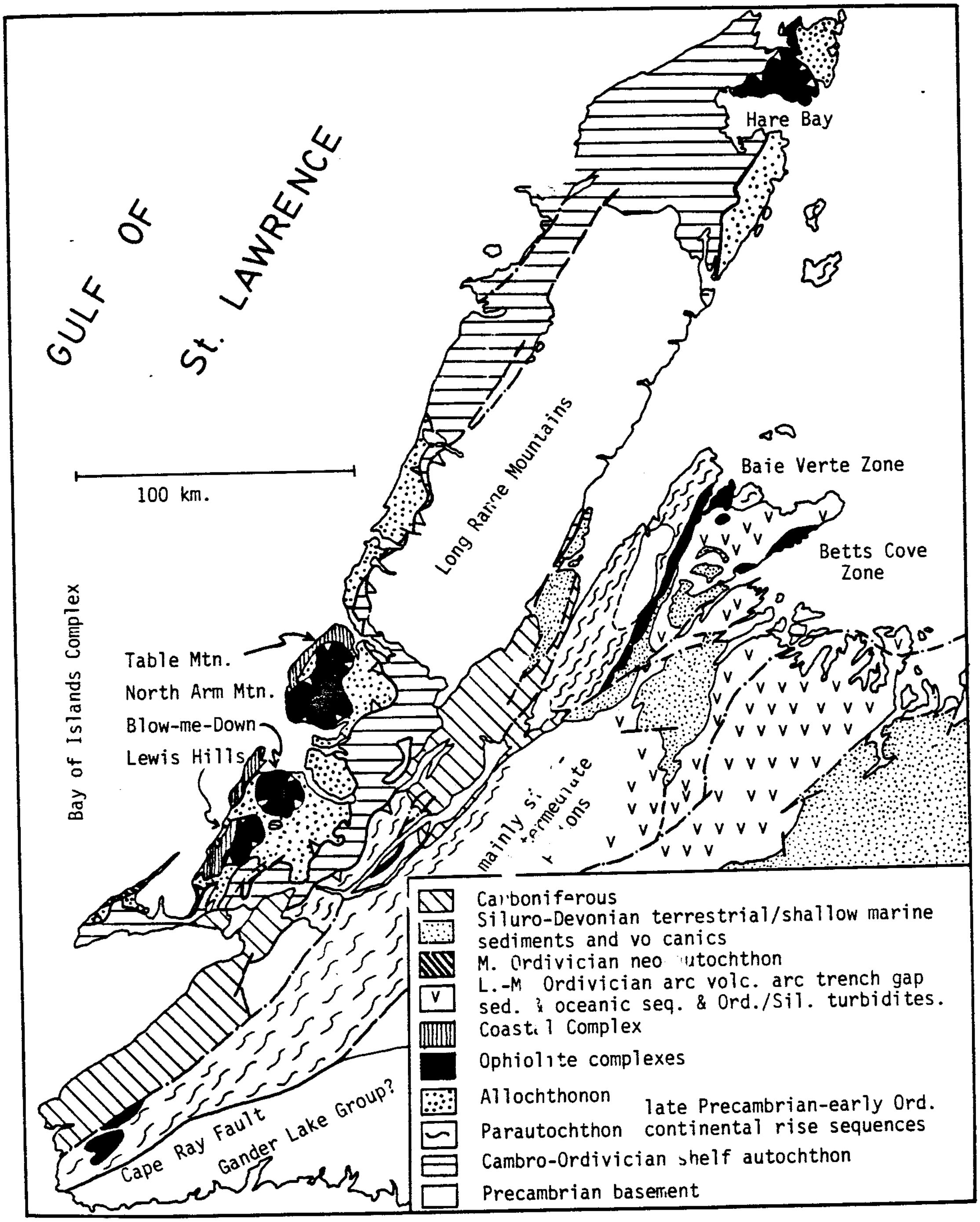
Access to the northern and western faces of the mountain is provided by Route 44 and several unnamed jeep trails running up to saw mills along Lower Trout River Pond. The southern wall is accessible by boat along the ponds and then by an invigorating scramble up 50-150 meters of talus. The eastern margin of the massif may be reached either by foot from Winter House Brook or by boat from the eastern end of Upper Trout River Pond.

Having conquered the roads, water and relief, a researcher is well advised to have previously registered with the Park Superintendent in Rocky Harbor. A sampling permit is required but fossils, travertine and xonotlite may never be collected.

Physiography and Exposure

The most striking features of the northern exposures of the Bay of Islands Ophiolite are 1) the abrupt relief of Table and North Arm

Figure I-1. Generalized regional geologic and tectonic map of western Newfoundland (after Karson and Dewey, 1978).



GULF OF
St. LAWRENCE
Hare Bay
100 km.
Baie Verte Zone
Betts Cove
Zone
Bay of Islands Complex
Table Mtn.
North Arm Mtn.
Blow-me-Down
Lewis Hills
Cape Ray Fault
Gander Lake Group?
Carboniferous
Siluro-Devonian terrestrial/shallow marine
sediments and volcanics
M. Ordivician neoautochthon
L.-M Ordivician arc volc. arc trench gap
sed. & oceanic seq. & Ord./Sil. turbidites.
Coastal Complex
Ophiolite complexes
Allochthonon
Parautochthon
late Precambrian-early Ord.
continental rise sequences
Cambro-Ordivician shelf autochthon
Precambrian basement

Mountains and 2) the absolutely barren exposures of the ultramafic suite of Table Mountain. To the east of the massifs are low rolling hills which are densely covered with spruce, fir and birch. These are generally underlain by the sedimentary units of the Humber Arm Allochthon, although several blocks of volcanics also crop out as knobby hills with variable vegetation. To the west of the mountain are the hills of the Coastal Complex. Vegetation is fairly thick but variable in density.

Table Mountain itself (see frontpiece) has up to 600 meters of vertical relief capped by a flat-lying plateau. The highlands of the massif are dominantly covered by felsenmeer, although to the west, ridges of gabbro and troctolite crop out. String bogs are abundant in the lowlands. Stream and fault valleys radiate away from the summit in the middle of the harzburgites (Plate A).

The expected lithologies correlate directly with the type and density of vegetation growing on them. The ultramafic suite has virtually no soil or regolith cover. Vegetation is rare and confined to joints and the peat layers of the string bogs and snow ponds. The gabbroic rocks, however, are typically covered with small shrubs and stunted evergreens showing Krumholtz morphology (locally termed "Tuckamore").

Rock exposure is continuous along the northern, eastern and southern margins of the mountain. Talus has buried the basal exposures along all margins of the massif. Outcrops on the plateau are primarily limited to low ridges and stream cuts. Blocks within the felsenmeer may reach 10 meters across, so care must be taken to identify rock that is in situ. Exposure of the mafic cumulates is excellent along ridges, stream cuts and glacial cirques.

Mapping Techniques

Mapping was conducted on mylar overlays of aerial photographs with an approximate scale of 1:15,840 obtained from the Department of Forest Resources and Lands, St. Johns, Newfoundland. Stereographic interpretation of some of the large scale features was undertaken and then verified in the field. A base map was made by enlarging the Trout River and Lomond sheets of the 1:50,000 series of topographic maps issued by the Department of Energy, Mines and Resources to a scale of 1:15,840. The drainage (corrected for topographic distortion) was transferred from Forest Inventory Maps (Forest Type Map) issued at a scale of 1:15,840 by the Newfoundland Forest Service, St. Johns. Field data was then transferred from the aerial photo overlays to the base map. Outcrop domains were not mapped along the northern face of the massif because of the 100 percent exposure. They were recorded only where limited exposure interfered with observation. The location of Route 44 on this map is only approximate as upgrading, including minor relocation, is currently underway along the section connecting Woody Point and Trout River.

Field Work

Three and one half months of detailed structural and lithologic mapping was undertaken during the summers of 1980 and 1981. A total area of approximately 40 km^2 was mapped. The primary objective of this work was to complete a detailed structural traverse through the tectonized units exposed on the mountain. A complete suite of some 100 oriented and unoriented samples was collected and shipped to Montreal by boat.

During the 1980 Field Season, Roger Powers, a SUNYA undergraduate, accompanied the author as a field assistant.

Laboratory Technique

Oriented samples were gathered in the field for later petrofabric analysis. Due to the intense serpentinization (up to 70%) of the rock, 1 to 3 kilogram samples were collected when possible. This size of sample is quite difficult to securely manipulate in multi-axis sample holders so plasticene was used to fix samples reoriented in the lab. Sets of rock chips were cut parallel to the recorded foliation and perpendicular to the foliation and parallel to spinel/enstatite lineations. A Leitz 5-axis universal stage was used to obtain the olivine fabric data. Standard stereographic manipulation of the data was then undertaken. The reader is referred to an excellent summary of this technique in Nicolas and Poirier (1976).

CHAPTER II

REGIONAL GEOLOGY OF WESTERN NEWFOUNDLAND

Newfoundland has been separated into three major geological terranes: 1) the Western Platform, 2) the Central Mobile Belt, and 3) the Avalon Platform. This discussion will only be concerned with the Western Platform or Humber Zone (Williams, 1976). The eastern boundary of this terrane is defined by the Baie Verte Lineament (Kidd, 1974) while the westernmost extent of Appalachian deformation constitutes its opposite border (Williams et al, 1977). This zone may be separated into five distinct units: 1) a Precambrian crystalline basement, 2) autochthonous Eocambrian to early Cambrian shallow water clastics, 3) parautochthonous flysch and shelf facies, 4) the allochthonous assemblage, and 5) a neoautochthonous clastic assemblage (Figure I-1).

The scope of the following brief summary of the geology of the Western Platform is limited in order to concisely give the reader a general perspective of the stacking order of the allochthonous slices and current interpretation of the tectonic evolution of Western Newfoundland. More extensive discussions of regional geology and interpretations may be found in Stevens (1970), Williams (1975) and Casey (1980).

Basement Complex

The basement complex is exposed in the Indian Head and Long Range Mountains as well as in the western Fleur de Lys Terrane (Bursnall and DeWit, 1975). It is typified by poly-deformed gneiss and schists, anorthosite and foliated granites. Isotopic dating of the granites has given ages ranging from 1130 ± 90 ma. (Rb-Sr whole rock) to 840 ± 20 ma. (biotite isochron) (Pringle et al, 1971). Strong and Williams (1972) noted NE trending tholeiitic dikes crosscutting the crystalline basement. Using $^{40}Ar/^{39}Ar$ ratios to date dike samples collected from the eastern margin of the Great Northern Peninsula approximately 100 km south of Hare Bay (Figure I-1). Stukas and Reynolds (1974) suggested that 805 ± 35 ma. was a minimum age for intrusion. Several papers have related these dikes with volcanism generated during the Early Cambrian rifting of eastern North America (Strong and Williams, 1975). The age and geographic distribution of the basement complex of the Western Platform support its correlation with the Grenville Province.

Autochthonous Sedimentary Units

The autochthonous clastic assemblage which unconformably overlies the crystalline basement is exposed on Belle Isle (Williams and Stevens, 1969) and in the Port au Port region (Whittington and Kindle, 1969; Stevens, 1970; Bergstrom, et al, 1974). On Belle Isle the lowest stratigraphic unit, the Bateau Formation, is composed of a series of conglomerates, quartzites, arkosic sandstones, siltstones and shales. The basal conglomerates and sandstones were derived from the Grenville basement. Mafic dikes cut through this unit to feed the overlying Lighthouse Cove volcanics. Stukas and Reynolds (1974) have reported a $^{40}Ar/^{39}Ar$ date of 605 ± 10 ma. for the feeder dikes. In turn, the volcanics are overlain by the Bradore Formation. The pebble conglomerates and arkosic sandstones comprising this unit have preserved current structures indicating a northern and northwestern provenance. The Forteau Formation conformably overlies these clastics and consists of dolestones, fine bedded gray shale and argillite. Trilobites recovered from the upper section of this formation give a minimum late early Cambrian age.

Limestones and dolestones gradually become interbedded with the clastics progressively up-section. The Hawkes Bay Formation is dominantly composed of quartz arenites while the overlying Cloud Rapids and Traytown Pond Formations contain some carbonates.

On Belle Island, these units are in fault contact with overlying assemblages, while around Port au Port the conformable transition into dominantly carbonate assemblages is preserved. These shelf carbonates range in age from middle Cambrian to Llanvirnian (Whittington and Kindle, 1969; Bergstrom, et al, 1974). A thick sequence of shales and greywackes conformably overlies the carbonates. This unit is known as the Goose Tickle Formation and has paleontologically-determined ages of Llanvirnian to Llandeilian. Stevens (1970) has argued that these sediments have an easterly provenance and that the lithologies may be correlated with sequences preserved in the overlying allochthons. This flysch succession coarsens upward and is in fault contact with the allochthonous units.

Parautochthonous and Neoautochthonous Assemblages

Stevens (1970) and Williams and Godfrey (1980) have identified slices of shelf facies, shales or flysch within the allochthon which were originally deposited on the autochthonous continental shelf. These are termed parautochthonous as they have been interpreted to have undergone smaller amounts of transport than the major thrust slices.

The Humber Arm Allochthon is unconformably overlain by limestones, silty shales, sandstones and redbeds. These are exposed on the Port Au Port Peninsula. The maximum age of these sediments is given by a paleontological date of Early to mid Caradocian (Stevens, 1976). This date represents a minimum age for the final emplacement of the allochthon.

Allochthonous Terranes

Williams (1975) reviewed the stratigraphic and structural succession of the two transported complexes of western Newfoundland. These are the Hare Bay and Humber Arm Allochthons (Figure I-1). Both are composed of five or six individual and lithologically distinct thrust slices. Williams interpreted the stacking order and nature of internal juxtaposition to mean that slices were successively added to the base of the allochthon as it progressed westward across the shelf.

The Hare Bay Allochthon is composed of six slices. From bottom to top these are the Northwest Arm Slice, the Maiden Point Slice, the Grandois Slice, the Milan Arm Melange, the Cape Onion Slice, and finally the St. Antony Slice. The basal sheet (Northwest Arm) may be directly correlated with the lowermost slice of the Humber Arm Allochthon on the basis of graptolite occurrences and similar lithologic composition. Likewise, the Cape Onion Slice, which consists of mafic pillow lavas, mafic volcaniclastics, and minor black shale, shows distinct similarity with the Skinner Cove Slice of the Humber Arm Allochthon. A more complete discussion of the Hare Bay Complex may be found in Williams (1975).

The Humber Arm Allochton is composed of five slices. From top to bottom they are the Humber Arm, Skinner Cove, Old Man Cove, Little Port and Bay of Islands slices. The lithologies and ages of each slice will be briefly reviewed.

The Humber Arm Assemblages may be divided into two facies-equivalent groups. Those outcrops occurring north of Bonne Bay are within the Cow Head Group (Kindle and Whittington, 1958) while those to the south belong to the Curling Group (Stevens, 1970). The fossil record of both units indicates that they cover the same time range (Middle Cambrian through late Arenigian). The Curling Group is composed of westerly-derived quartzo-feldspathic flysch (the Summerside and Irishtown formations). These are overlain by interbedded shales, limestones and minor limestone breccias (the Cooks Brook and Middle Arm Point formations). Williams (1975), following

Bird and Dewey (1970) without acknowledgement, has interpreted this division as relating the blocking off of the westerly provenance by the carbonate bank upon maturity of the continental margin. The upper division of this group is composed of quartzo-feldspathic flysch containing sparse ophiolitic detritus and hence presumably was derived from the east. This flysch (the Blow Me Down Formation) is late Arenigian in age (Stevens, 1981, personal communication to W. Kidd) and provides the last record of conformable sedimentation on the continental rise (Casey, 1980).

The Cow Head Group is composed of coarse limestone breccias, shales and turbidites. It has been considered to be a proximal facies (Stevens, 1970; Hubert et al, 1977) while the Curling Group is the thicker section of the clastic rise prism of a continental margin.

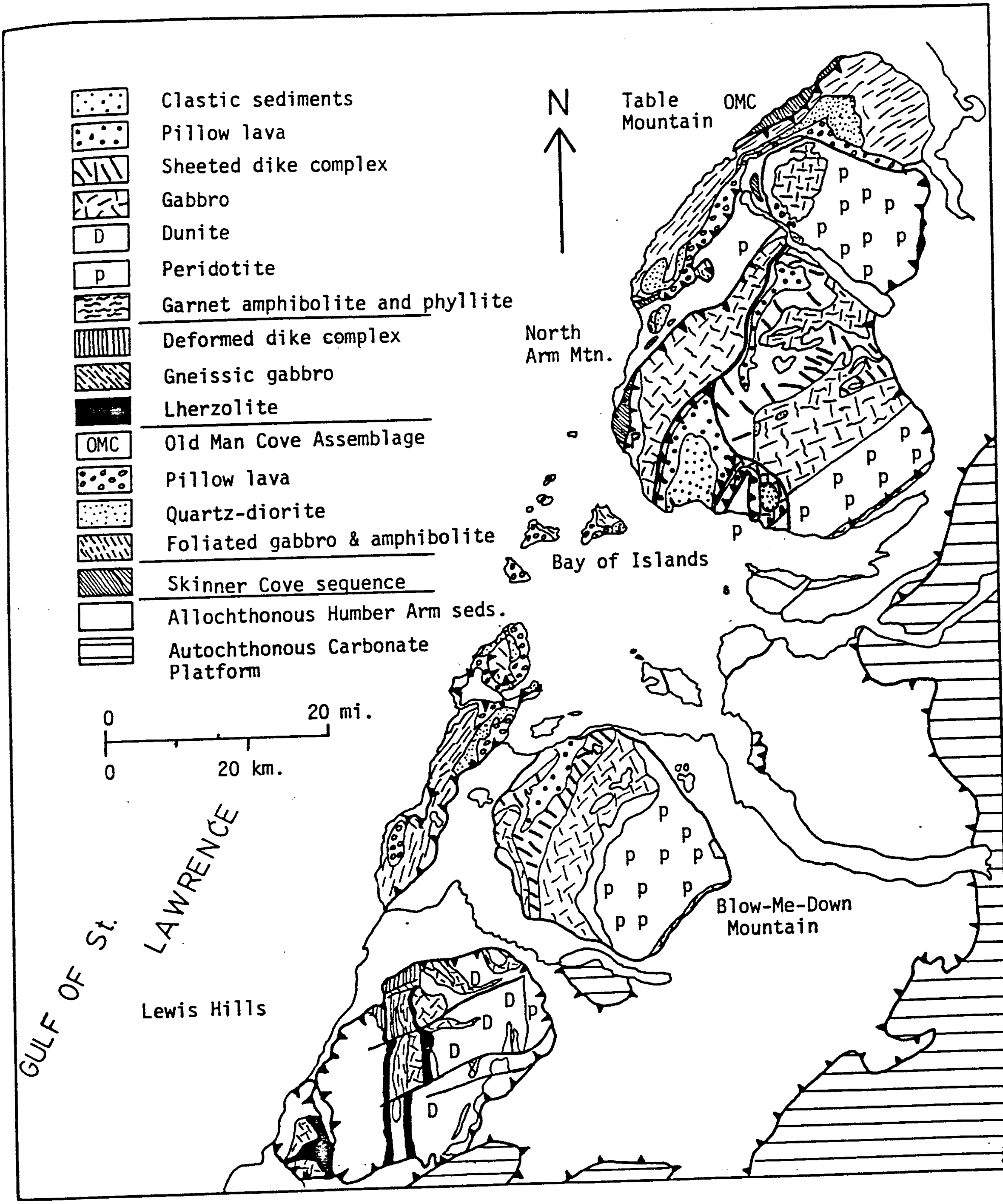
The Coastal Complex

The Coastal Complex has been interpreted as consisting of three separate thrust assemblages. From base to top these are the Skinner Cove Assemblage, the Old Man Cove Assemblage and the Little Port Assemblage (Williams, 1973, 1975; Figure II-1). The lithologies and structural characteristics of each unit will be reviewed and the arguments of Church (1976) and Karson and Dewey (1978) against the previously suggested stacking order will be addressed.

Skinner Cove Assemblage

This unit is composed of remarkably unaltered and relatively undeformed mafic pillow lavas, mafic breccias, latitic flows, gray

Figure II-1. Geology of the Bay of Islands Region. Northern part after Williams (1973), Casey and Kidd (1981) and Smith (1958). Lewis Hills after Karson (1977).



Clastic sediments
Pillow lava
Sheeted dike complex
Gabbro
D Dunite
p Peridotite
Garnet amphibolite and phyllite
Deformed dike complex
Gneissic gabbro
Lherzolite
OMC Old Man Cove Assemblage
Pillow lava
Quartz-diorite
Foliated gabbro & amphibolite
Skinner Cove sequence
Allochthonous Humber Arm seds.
Autochthonous Carbonate Platform
0
20 mi.
0
20 km.
N
Table Mountain
OMC
North Arm Mtn.
Bay of Islands
Blow-Me-Down Mountain
Lewis Hills
GULF OF St. LAWRENCE

and red shales, and minor limestone. The age of the unit is poorly constrained but is Late Cambrian to Early Ordovician (Williams, 1975).

Old Man Cove Assemblage

This assemblage was recognized by Williams (1975) and consists of poly-deformed greenschists with minor carbonate layers. A steeply dipping penetrative foliation has an approximate northeastern trend. Undeformed mafic dikes crosscut the assemblage but are in integral part of the slice. Williams (1975) argued that the Old Man Cove Assemblage had a separate origin from that of the Skinner Cove Assemblage. More recent work by Karson (1977 and personal communication) and Idleman (in preparation) has shown that deformed and undeformed ankaramite dikes have been identified in each slice. Transitional and apparently conformable contacts between the two assemblages have been observed near Lewis Hills and along the southern side of Bonne Bay.

Little Port Assemblage

The Little Port Complex is a narrow band of slices exposed along the coast from Bonne Bay to Little Port (Figure II-1). The observed lithologies include foliated and layered gabbros and amphibolites, mafic to silicic volcanics and peridotites cut by deformed and undeformed mafic dikes. Intrusive bodies of trondjhemite, hornblende gabbro and quartz diorite are also present. The dikes and volcanics are virtually undeformed, strongly implying a poly-genetic history for the Little Port Assemblage. No well-defined thrust contacts (as described by Williams, 1975) have been observed separating the Little Port from the adjacent assemblages. An autochthonous relationship between the slices of the Coastal Complex has been proposed by Karson (1977) and Karson and Dewey (1978). More recent detailed mapping around the village of Trout River has yet to clearly confirm this (Idleman, in preparation; Karson, personal communication).

Bay of Islands Assemblage

Williams (1975) groups the following massifs in the highest structural slice of the Humber Arm Allochthon - Table Mountain, North Arm Mountain, Blow Me Down Mountain and the Lewis Hills. The internal structure of each of the massifs is remarkably intact and only minor rotations of structural elements are observed between the individual massifs (Figure II-1).

The base of each massif displays a contact dynamothermal aureole (Jamieson, 1979) overlain by a thin tectonized ultramafic suite which shows distinctive structures indicative of intense strain associated with overprinting of a previous penetrative fabric. Progressively up section in each massif, a suite of tectonized harzburgites and dunite occurs. This unit has a variable inferred pseudo-stratigraphic thickness from 4 to over 7 km. Above this, deformed and undeformed cumulate rocks are exposed on all of the massifs. Intrusive diabase dikes are observed cutting isotropic gabbros on all massifs except Table Mountain. Pillow lavas and sheeted dike complexes are best preserved on North Arm and Blow Me Down although some volcanics and dikes occur in the Lewis Hills.

Parallochthonous Sediments

Casey and Kidd (1981) have recently described a group of sedimentary breccias in distinct angular unconformity with the North Arm Massif ophiolite. They interpret this group (Crabb Brook Group, new name) as having been deposited on the ophiolite during its obduction and therefore it is distinct from other allochthonous or autochthonous groups.

Radiometric Dating of Ophiolite Formations

Mattison (1975, 1976) has reported on U-Pb isotopic dating of zircons recovered from separations of trondhjemite collected from the gabbroic unit of Blow Me Down Mountain, and from the Coastal Complex exposures immediately north of Trout River. His results give ages of 504 ± 10 ma. and 508 ± 5 ma. respectively. These dates, however, were calculated with old decay constants. Van Schmus (personal communication) observed that, in general, the correction factor for Precambrian rocks corresponds to about 1½ percent (corrected age being younger). Therefore, the 508 ma. date for the plutonic suite of the Bay of Islands Complex is a maximum age. Jacobson and Wasserberg (1979) have reported two Sm-Nd isochrons for pyroxene gabbros samples from Blow Me Down Mountain. These give crystallization ages of 508 ± 6 and 501 ± 13 ma.

Timing of Obduction

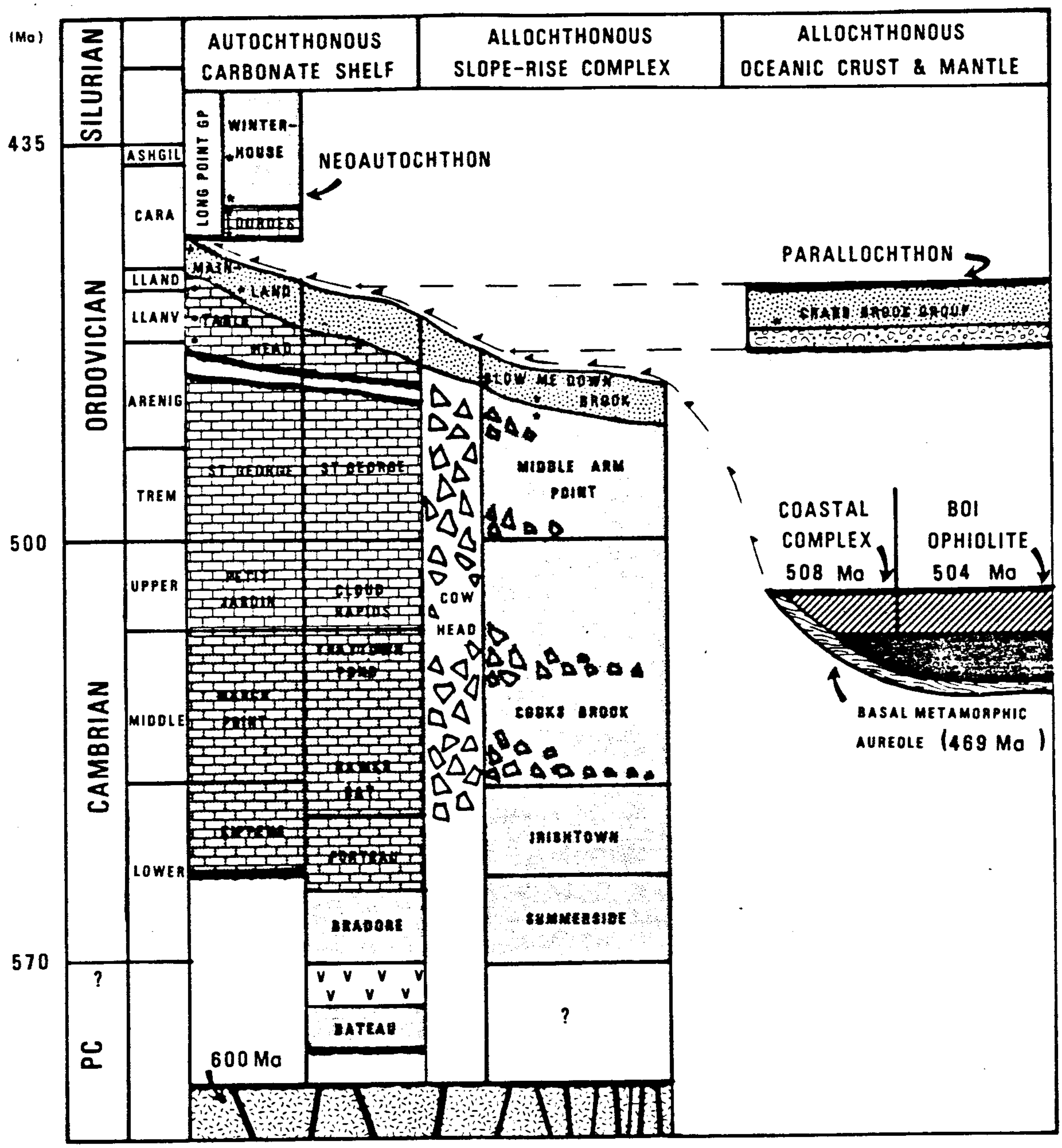
Initiation and final emplacement of the Bay of Islands Ophiolite is constrained by K/Ar and $^{40}Ar/^{39}Ar$ dates of amphiboles collected from the metamorphic aureole at the base of the thrust slice, and by paleontological dates of the first flysch containing ophiolite detritus. The aureole rocks show textures indicative of deformation at high temperature and strain rates. This has led researchers to argue that it represents the initial mantle detachment zone (Williams and Smyth, 1973; Mercier, 1976). The K/Ar and $^{40}Ar/^{39}Ar$ dates range from 458 ± 10 to 469 ± 5 ma. (Archibald and Farrar, 1976; Dallmeyer and Williams, 1975; Dallmeyer, 1977). New sets of decay and abundance constants have since been published for the calculation of K/Ar dates (Dalrymple, 1979). Applying the correction factors to the ages gives a range of dates from 466 ± 10 to 478 ± 5 ma.

The stratigraphic constraints on the obduction of the Bay of Islands nappe onto the continental margin are given by a late Arenigian fossil in the earliest easterly-derived flysch which contains ophiolitic detritus (Stevens, 1970, 1976). The date of the final emplacement of the allochthon is bracketed by the age of the youngest autochthonous flysch adjacent to the Humber Arm Allochthon and by the neoautochthonous sequences deposited on top of the allochthon. Stevens (1976) reports that the ages of these units are nearly identical, hence dating the final emplacement of the allochthon as early Caradocian.

Regional Tectonic Interpretation

The regional geology discussed in the previous section has led to the generalized reconstructions schematically depicted in Figure II-2. In depth discussions of the continental shelf and slope/rise

Figure II-2. Restored generalized stratigraphic and structural relations of Upper Precambrian to Middle Ordovician assemblages of the Bay of Islands region. Fine stipple represents pre- or post-orogenic clastics; bricks denote carbonates; stippled bricks are interbedded carbonates and clastics; angular clasts are limestone breccias; coarse stipple synorogenic clastics. Arrows indicate sedimentary provenance direction while half arrows denote tectonic transport. Asterisks indicate fossil control; unconformities are shown by heavy lines. The ophiolite is graphically shown with mafic and ultramafic layers - no age difference is implied (after Casey and Kidd, 1981).



(Ma)
435
500
570
SILURIAN
ORDOVICIAN
CAMBRIAN
PC
ASHGIL
CARA
LLAND
LLANV
ARENIG
TREM
UPPER
MIDDLE
LOWER
?
AUTOCHTHONOUS CARBONATE SHELF
ALLOCHTHONOUS SLOPE-RISE COMPLEX
ALLOCHTHONOUS OCEANIC CRUST & MANTLE
LONG POINT GP
WINTER-HOUSE
NEOAUTOCHTHON
PARALLOCHTHON
MAIN-LAND
HEAD
BLOW ME DOWN BROOK
ST GEORGE
MIDDLE ARM POINT
COAST COMPLEX 508 Ma
BOI OPHIOLITE 504 Ma
CLOUD RAPIDS
COW HEAD
COOKS BROOK
BASAL METAMORPHIC AUREOLE (469 Ma)
IRISHTOWN
SUMMERSIDE
BRADORE
BATEAU
600 Ma

assemblages, as well as the juxtaposition of allochthonous material, may be found in Stevens (1970, 1976) and Williams (1971, 1975, 1979).

Casey (1980) addressed the problem of the location and polarity of the Iapetus subduction zone responsible for the assemblage of western Newfoundland. As he noted, the minimum distance which the Bay of Islands Complex was transported may be approximated by the distance from the leading edge of the complex to the eastern limit of Grenville Basement (DeWit, 1974), or the distance to the nearest suture zone lying to the east, the Baie Verte-Brompton Zone (Williams, 1977). These give values of at least 80 to 150 km.

A majority of tectonic reconstructions of the formation of western Newfoundland infer that the oceanic crust obducted to form the Bay of Islands Complex was originally in close proximity to the continental margin (Dewey and Bird, 1971; Karson and Dewey, 1978; Malpas, 1979). Casey (1980) discussed a number of observations which are apparently incompatible with the formation of the Bay of Islands Complex from oceanic crust which is proximal to a continental margin. These included a large difference in ages between the age of rifting and the age of obducted slab, as well as the nearly perpendicular relationship between the inferred extension direction (as indicated by dike trends in Grenville Basement) and the paleo-continental margin. In other analogous cases (e.g. the rifted margin between the southeastern United States and Mauritania), the dike trends may parallel or be highly oblique to the continental margin, but they are approximately the same age as the transitional oceanic crust (deBoer and Snider, 1979).

Casey (1980) proposed a model for the tectonic evolution of western Newfoundland which requires the initiation of an eastward-dipping subduction zone by Early Arenigian. This progressively consumes oceanic crust lying to the west, and hence adjacent to the eastern continental margin of North America. The Bay of Islands Complex is proposed to lie to the east of this zone with a configuration of parent ridge and transform segments compatible with that proposed by Karson and Dewey (1978). Casey's model predicts the occurrence of Lanvirnian intrusives within the oceanic crust which would be the result of subduction-related magmatism.

It is beyond the scope of this thesis to discuss the regional diversity and along-strike variations which lend themselves to a variety of tectonic reconstructions. The reader is referred to Casey (1980) and Williams (1979) for a discussion of this.

CHAPTER III

PETROGRAPHY

Introduction

Studies of the plutonic section of the North Arm Mountain Massif by Casey (1980) and Sullivan (1981) have cited textural and chemical (both bulk rock major and trace element) evidence that the majority of the lower cumulate rocks originated as adcumulates. Meso- to orthocumulate textures occur only near the top of the plutonic assemblage. The undeformed portions of the cumulates are characterized by xenomorphic granular textures with extremely rare mesostasis phases. Mosaic textures are typical of the monomineralic rocks.

Casey described a variety of textures, primarily within small-scale laterally discontinuous compositional layering, which were impossible to explain using the mechanisms invoked by Wager et al (1960) (i.e. crystal settling and adcumulate growth). George (personal communication) also observed perplexing textures in the cumulate suite of the Troodos Ophiolite. These included an undeformed chromite net texture encasing strongly lineated olivine crystals. Casey (1980) argued that in situ crystal nucleation and differentiation of melt could produce such textures in fine-scale layers along the bounding surfaces of the magma chamber.

The deformed or meta-cumulate sections of ophiolites have had their primary cumulate textures overprinted to varying extents by fabrics resulting from high temperature plastic deformation. The deformation has been shown, in some instances, to increase in intensity in the lower cumulates to the point where relict cumulate textures become extremely rare (George, 1978; Quick, in press). Complete overprinting of the original textures often results in the development of porphyroclastic or equigranular textures.

The residual nature of the tectonized harzburgites has been clearly established on chemical and textural criteria (e.g. Mercier, 1976; Quick, in press). Mercier and Nicolas (1975) examined textures of tectonized peridotites recovered from ophiolites and xenoliths. They proposed that the oldest preserved texture was protogranular and that a cycle of textural evolution existed with protogranular texture evolving into a loop from porphyroclastic to equigranular textures.

This chapter will examine the petrographic characteristics of the transitional dunites lying at the base of the deformed cumulates and also commonly found in the upper tectonized harzburgite. In addition, the harzburgite section exposed on Table Mountain will be subdivided into petrographic units on the basis of the presence of intercumulus phases and also on textural gradations.

Transitional Dunites

The thickness and quality of exposure of this unit are quite variable on Table Mountain. The southern exposures of dunite (just above the "Narrows" of Trout River Ponds) are approximately 400 meters thick yet the unit apparently pinches out along the northern face of the massif (Plate A). A suite of over a dozen samples covering all levels within the dunites was compiled by combining traverses along both faces of the mountain.

The dunites typically display tabular equigranular textures as defined by Mercier and Nicolas (1975) (Figure III-1). True equigranular mosaic texture is never fully developed. The original grain size ranges from 1 to 6 mm, although pervasive serpentinization has left isolated fragments of unaltered olivine which average about ½ mm in diameter. The original grain boundaries have been consumed by serpentinization and are occasionally outlined by magnetite "dust" and systematically oriented fibrous aggregates of serpentine. These boundaries were curvilinear with moderate to poor development of 120° triple points. Some samples have a bimodal grain size distribution with tabular grains (up to 4:1 aspect ratios) generally having deformation bands or subgrain boundaries oriented perpendicular to the elongation, and distinctly smaller equant olivine crystals. Other samples show a transitional texture with equant crystals ranging up to 5 mm across. The proportion of tabular to equant grains is also variable. These variations in texture show no systematic evolution with respect to structural level within the dunite unit.

The mineralogy of the dunites shows changes possibly controlled by structural level. The contact between the dunites and the overlying deformed ultramafic cumulates is gradational (see Chapter IV). The uppermost dunite samples examined contain up to 2 percent intercumulus clinopyroxene and as much as 2 percent highly altered patches

Figure III-1 (A: plane polarized light, B: crossed nicols)

Tabular equigranular texture in a spinel dunite sampled from the center of the transitional dunite exposure along the southeast margin of the cumulate carapace (Plate A). Elongated olivine crystals weakly define the trace of the S_1 foliation which dips about 40° to the right in the photographs. This sample is approximately 40% serpentinized with a weak serpentine mesh cross cutting the foliation. The spinel shows a moderate alignment along the trace of the foliation. Field of view is approximately 2½ cm across.

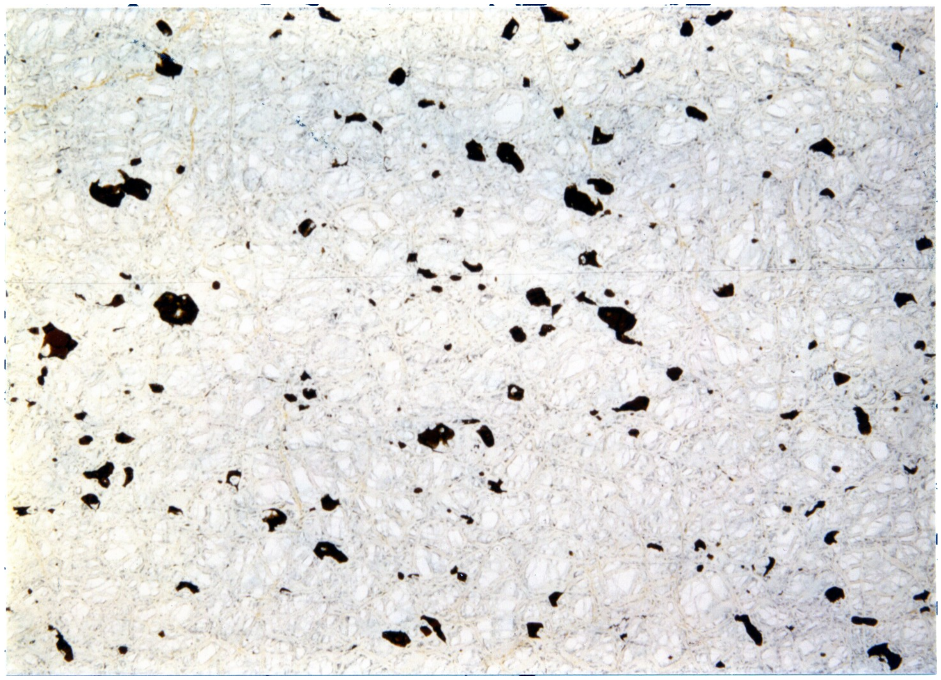


Figure III-1A: View in plane polarized light.

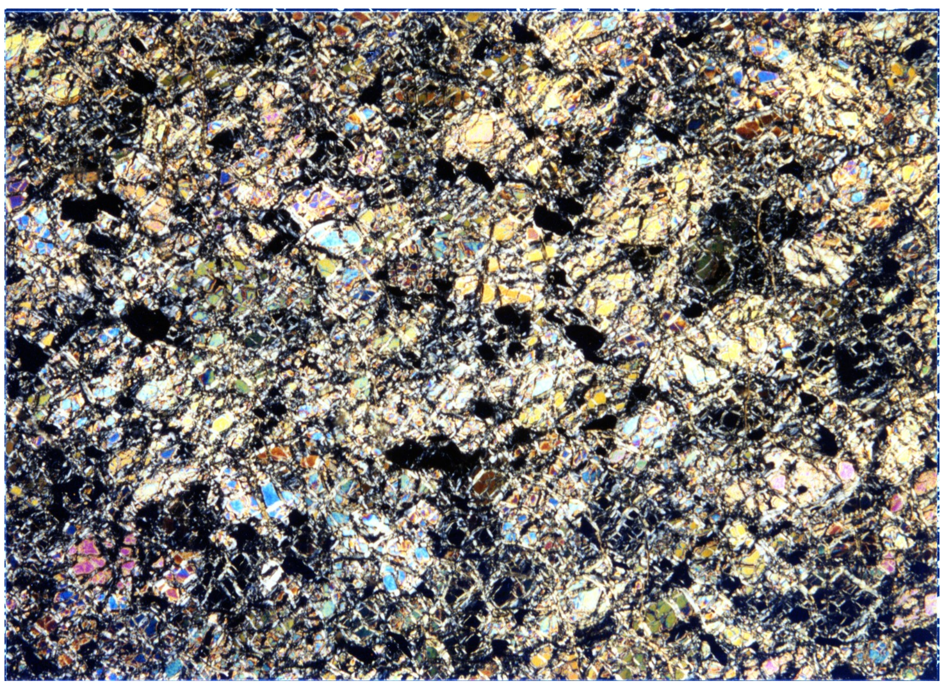


Figure III-1B: View in cross-polarized light (crossed nicols).

Tabular equigranular texture in a spinel dunite sampled from the center of the transitional dunite exposure along the southeastern margin of the cumulate carapace (Plate A). Elongated olivine crystals weakly define the trace of the S_1 foliation which dips about 40º to the right in the photographs. This sample is approximately 40% serpentinized with a weak serpentine mesh cross cutting the foliation. The spinel shows a moderate alignment along the trace of the foliation. Field of view is approximately 2.5 cm across.

of intercumulus plagioclase. In nearly all instances, the plagioclase has been completely replaced by a variety of hydrogrossular with traces of sericite and possibly clinozoisite. Although only three samples were examined from the middle of the dunite section, none contained intercumulus plagioclase and only trace amounts of clinopyroxene was noted. Intercumulus "blobs" of altered plagioclase and clinopyroxene apparently reappear toward the transitional contact of the dunites and residual harzburgites.

Serpentinization has strongly affected these rocks. Anastomosing veinlets of fibrous serpentine form a penetrative mesh in thin sections representing, on average, 35 to 60 modal percent of the rock. One sample is completely serpentinized.

The characteristics of the individual mineral phases are briefly discussed below. Particular attention is given to microstructural features because any evidence of fabric evolution or overprinting is largely confined to individual grains due to extensive serpentinization.

Olivine: The crystals are subhedral and have variable proportions of tabular and equant grains. The grain boundaries are curvilinear with minor embayments along some of the more highly strained crystals. Micro inclusions are preserved in less than 1 percent of the olivine. These usually occur in linear trails confined to specific planes within the crystal. The inclusions appear to be solid as some are preserved in the serpentine engulfing the crystals. For the most part, the grains are optically positive and the 2 V is around 90°, suggesting that the composition lies within the crysolite range. The structures indicating deformation of the crystal lattice are listed in order of occurrence: undulatory extinction, deformation bands/subgrains, kink bands, deformation lamellae and twins.

Clinopyroxene: Usually occurs in anhedral cuspate forms within the interstices between olivine crystals. They are seldom larger than ½ mm. These blebs may also possibly occur in spaced clusters of several grains. Magnetite and possibly iddingsite frequently occur in conjunction with the pyroxene. Undulatory extinction is common, although some unstrained crystals are also preserved. Possible traces of talc are observed in conjunction with serpentine along the margins of the pyroxenes.

Spinel: Occurs as subhedral to euhedral, rusty brown to yellowish rusty brown grains smaller than ½ mm. Irregular octahedral cleavage traces are often accentuated by microcrysts of magnetite which appear to nucleate against the spinel and often partially rim it.

Plagioclase: This is rarely preserved within the center of euhedral cuspate to amoebic forms. It has been replaced with a dirty brown material composed mostly of hyrogrossular and minor amounts of sericite and possibly extremely fine-grained clinozoisite or epidote. When preserved, it appears to be unstrained. No twinning was observed.

Serpentine Minerals: As in all samples collected from Table Mountain, the serpentine grains display two habits. The general penetrative serpentinization is composed of fibrous serpentine showing mesh structure and occurring along anastomosing veinlets throughout the rock. Small patches of platy serpentine apparently replace the fibrous variety. Where this occurs, the material is a cloudy brown as opposed to a pale green. Mercier (1976) reports that the dominant composition is lizardite which may later transform to Fe-free chrysotile resulting in magentite dust along former olivine grain boundaries and platelets of opaques parallel to the low index crystallographic planes of pseudomorphed olivine. He also identified an antigorite-serpophyte which is likely the small secondary patches observed in thin section.

Transitional Harzburgite

While the harzburgite suite of Table Mountain may be subdivided into two major units on the basis of enstatite and spinel textures, the uppermost portion of the upper unit shows some transitional features with the overlying dunites. This harzburgite contains primary olivine (75-80%), enstatite (15%), spinel (<1 to 3%) and characteristic interstitial plagioclase (1-2%) and clinopyroxene (0-7%) (Figure III-2). Four sampling traverses proceeding down-section from the dunites exposed on the northern face of the massif are spaced several hundred meters apart. Samples were collected about every 25 meters. With this scale of sample control, it appears that intercumulus plagioclase is limited to a zone extending about 200 meters down-section from the dunite/harzburgite contact, while intercumulus clinopyroxene may occur up to 400 or 500 meters down-section. Harzburgites containing trace

Figure III-2 (A: plane polarized light; B: crossed nicols) Transitional harzburgite recovered from the north face of Table Mountain. The rock displays porphyroclastic texture and has two cuspate clinopyroxene grains (high relief, highly birefringant crystals) in the left half of the photos. In the lower right corner a lenticular patch of hydrogarnet is also visible (dark brown, isotropic mineral). The field of view is just under 1 cm across.

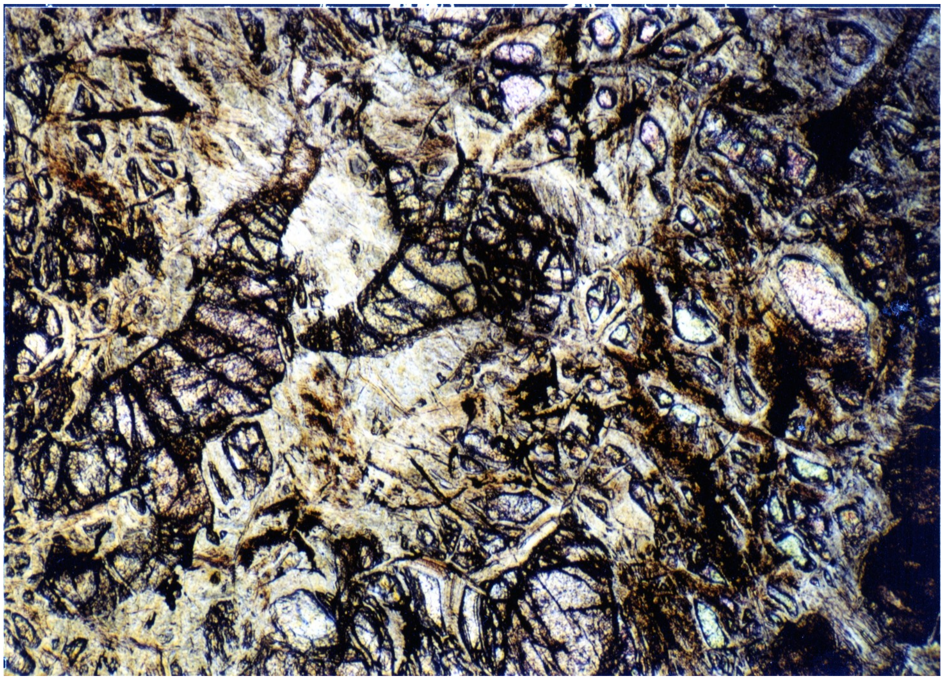


Figure III-2A: View in plane polarized light.

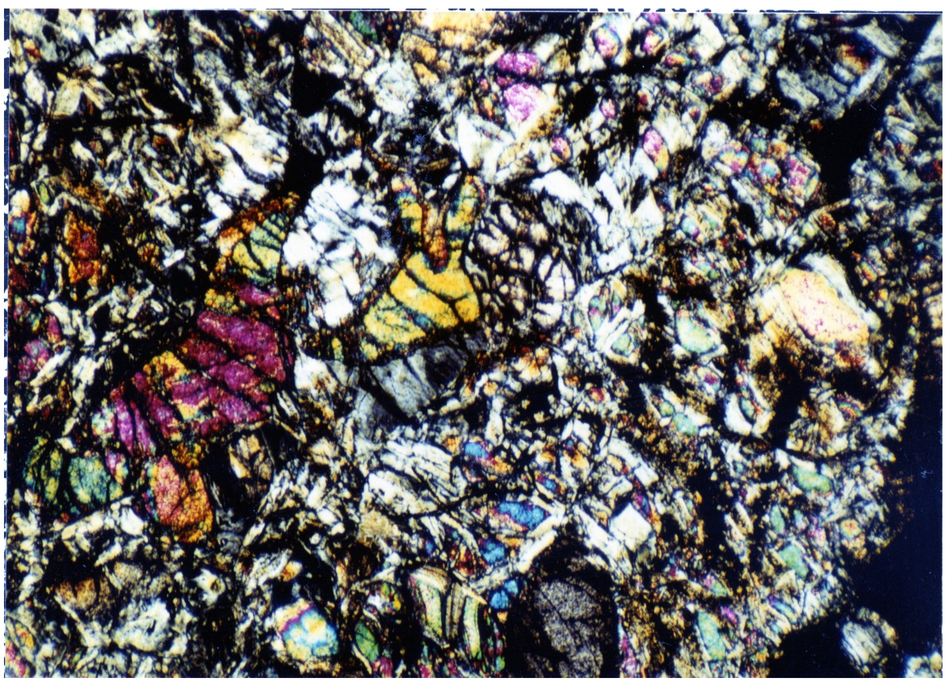


Figure III-2B: View in cross-polarized light (crossed nicols).

Transitional harzburgite recovered from the north face of Table Mountain. The rock displays porphyroclastic texture and has two cuspate clinopyroxene grains (high relief, highly birefringent crystals) in the left half of the photos. In the lower right corner a lenticular patch of hydrogarnet is also visible (dark brown, isotropic mineral). The field of view is just under 1 cm across.

quantities of interstitial plagioclase and clinopyroxene are here termed the transitional harzburgites.

The olivine, enstatite and spinel textures are consistent throughout the transitional and upper harzburgites. The rocks show variably developed porphyroclastic textures. Descriptions of individual mineral characteristics are given in the next section.

Upper Harzburgites

This unit comprises approximately the upper third of the harzburgites exposed on Table Mountain. It is strictly a petrographic unit as the penetrative structural elements show only a slight systematic variation throughout the massif. The harzburgites show variably developed porphyroclastic textures. Variations in this texture include changes in the ratios of equant to tabular olivine crystals, the average grain size of the equant olivine grains, and the sparse development of embayments along the curvilinear grain boundaries. Just such a sequence of textural changes were described by Mercier and Nicolas (1975). They proposed a cycling of textures resulting from ongoing strain and recrystallization of upper mantle peridotites. Further discussion of this cycle may be found in Chapter V.

The upper harzburgites are characterized by a pervasive [001] elongation of the tabular enstatite crystals (Figure III-3A). Individual spinel grains are also elongated parallel to the lineation defined by their aggregates.

Detailed descriptions of the constituent mineral assemblages are given below:

Figure III-3A (crossed nicols)

Photomicrograph of the porphyroclastic texture typical of the upper harzburgites. The moderate elongation of the enstatite crystals perpendicular to the observed cleavage traces is often indicative of the upper harzburgites. The trace of the foliation is nearly vertical in this photograph. Several tabular olivine crystals also show weak elongation parallel to the trace of the foliation.

Figure III-3B (crossed nicols)

Polycrystalline enstatite clot within the lower harzburgites. The cleavage traces of the uppermost grain are kinked at two points where the crystal makes contact with other grains in the cluster. The extensive bastite pseudomorphing of the large enstatite crystal to the right of the kinked grain is typical of the lower harzburgites.

Figure III-3A: View in cross-polarized light (crossed nicols).
Photomicrograph of the porphyroclastic texture typical of the upper harzburgites. The moderate elongation of the enstatite crystals perpendicular to the observed cleavage traces is often indicative of the upper harzburgites. The trace of foliation is nearly vertical in this photograph. Several tabular olivine crystals also show weak elongation parallel to the trace of the foliation.

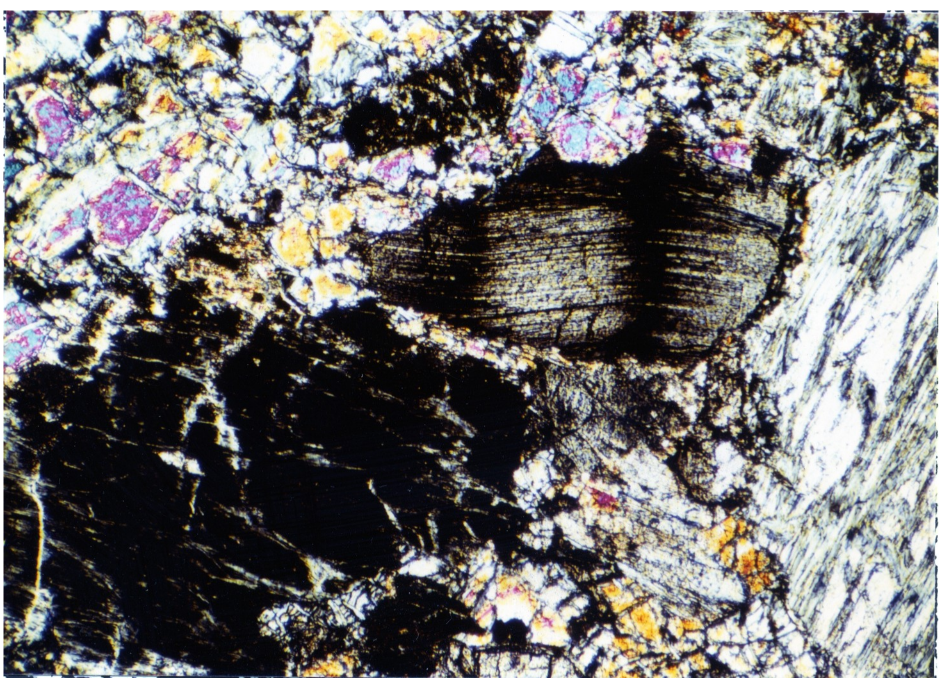


Figure III-3B: View in cross-polarized light (crossed nicols).
Polycrystalline enstatite clot within the lower harzburgites. The cleavage traces of the uppermost grain are kinked at two points where the crystal makes contact with other grains in the cluster. The extensive bastite pseudomorphing of the large enstatite crystal to the right of the kinked grain is typical of the lower harzburgites.

Olivine: The crystals are subhedral, have variably developed curvilinear grain boundaries and a majority show some evidence of strain. They have 2 V angles close to 90° and are usually optically positive, hence indicating that the composition falls within the crysolite domain. The deformation features preserved in the grains include (in decreasing order of abundance) undulatory extinction, deformation bands and/or subgrains, deformation lamellae and twins. Trails of micro inclusions which are usually restricted to planar domains within the crystals are quite rare, occurring in less than 1% of the grains.

Enstatite: It typically occurs as tabular subhedral grains that often show [001] elongation which results in a weak alignment of [001] with the aggregate lineations. The crystals typically show weak to moderate undulatory extinction although unstrained grains are not uncommon. Clinopyroxene exsolution lamellae paralleling cleavage traces occur in less than 20 percent of the crystals. Notably, bastite replacement and pseudomorphing is slight and is restricted to the periphery of, or along fractures cutting through the enstatite.

Enstatite commonly occurs in polycrystalline aggregates of 2 to about 10 grains. These clots may reach 1½ cm in length and often define the tabular enstatite lineation (see Chapter IV). The grain boundaries between the enstatites are somewhat rounded and weakly intergrown. Small (~¼ mm) olivine and spinel inclusions are noted within the enstatite.

Clinopyroxene: This mineral has two modes of occurrence. It may show a distinct interstitial relationship, lying within voids between olivine, or olivine and enstatite crystals. These clinopyroxenes are anhedral, cuspate and range up to ½ mm. By and large, they show little evidence of strain; about half of them show undulatory extinction. Quite often the interstitial material is more intensely altered than the neighboring enstatite. This alteration appears to act along the cleavage planes and, although cryptocrystalline, it may be uralitization.

The most common mode of occurrence of clinopyroxene involves the association of subhedral clinopyroxene with enstatite clots. The grain boundaries between the clinopyroxene and the enstatite are often slightly intergrown (Figure III-4). These grains usually show undulatory extinction and range up to 3/4 mm in size.

Spinel: This mineral occurs as subhedral (rarely anhedral or euhedral) grains that show elongation (up to 4:1 aspect ratios) parallel to the lineation defined by groups of spinel grains. It is rusty brown in color and rarely shows octahedral cleavage.

Alteration Products:

Serpentine Minerals: As was previously mentioned, the serpentine displays two habits. The penetrative serpentinization is composed of fibrous serpentine which shows minor recrystallization into platy aggregates. Magnetite dust is less common than in the dunites or transitional harzburgites.

Figure III-4 (A: plane polarized; B: crossed nicols)
Polycrystalline enstatite clot with a subhedral clinopyroxene crystal within an interstice along the clot's margin. The field of view is approximately 4 mm across.

Figure III-4 (C: plane polarized light; D: crossed nicols)
Polycrystalline enstatite clot with interstitial, anhedral clinopyroxene. This sample is from the lower harzburgites. Extensive bastite pseudomorphing has affected the enstatite while the clinopyroxene is quite fresh. The field of view is approximately 4 millimeters.

Figure III-4A: View in plane polarized light.

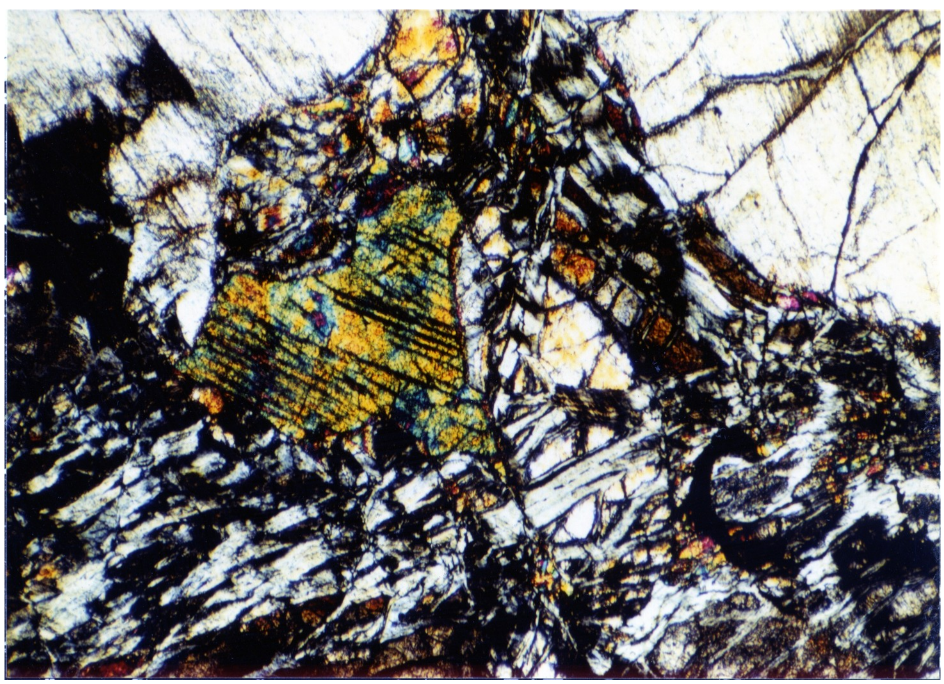


Figure III-4B: View in cross-polarized light (crossed nicols).

Polycrystalline enstatite clot with a subhedral clinopyroxene crystal within an interstice along the margin of the clot. The field of view is approximately 4 mm across.

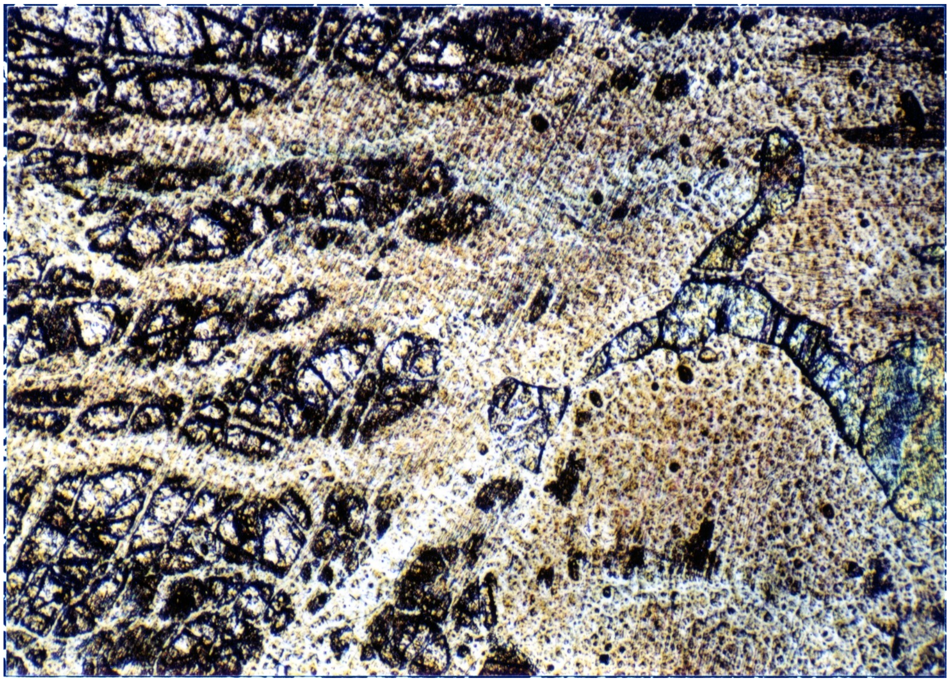


Figure III-4C: View in plane polarized light.

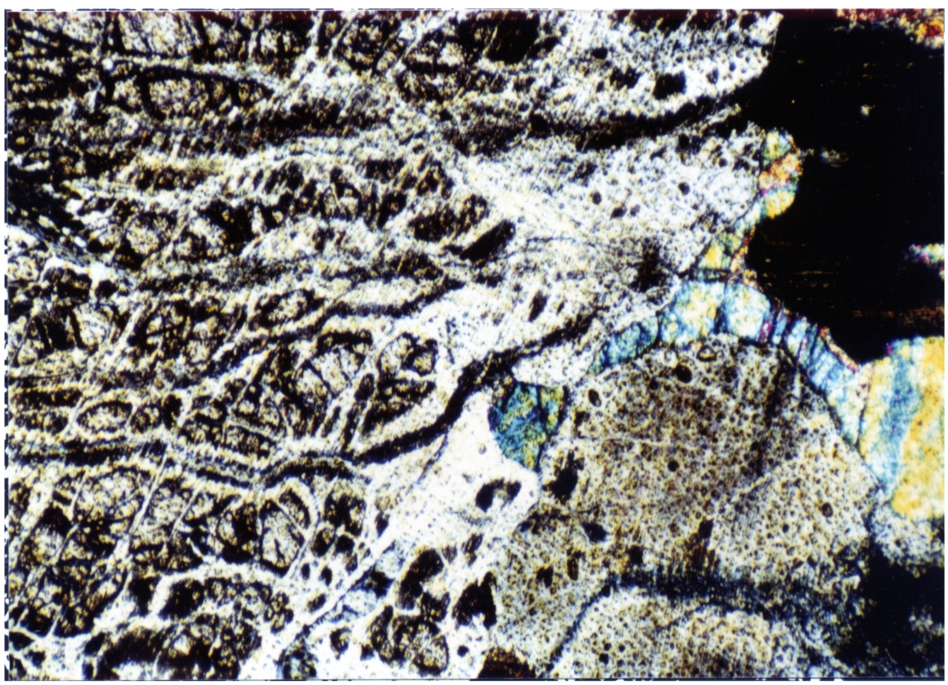


Figure III-4D: View in cross-polarized light (crossed nicols).

Polycrystalline enstatite clot with a interstitial, anhedral clinopyroxene. This sample is from the lower harzburgites. Extensive bastite pseudomorphing has affected the enstatite while the clinopyroxene is quite fresh. The field of view is approximately 4 mm across.

Talc: Traces of very fine-grained talc are seen with serpentine, usually in association with altered pyroxene.

Lower Harzburgites

The contact between the upper and lower harzburgites is gradational over approximately a 300 meter interval (Figure III-5). The harzburgites show no significant change in modal proportions of the primary minerals throughout these units. Neglecting serpentinization, Mercier (1976) reported that, on average, the harzburgites contained 76% olivine, 19% enstatite, 2% diopside and 3% spinel. This is in complete agreement with the results reported here, which were obtained by examining approximately 100 thin sections. This section concentrates only on the textural characteristics of the lower harzburgites.

Previous workers have recognized the change in enstatite texture within the tectonized harzburgites of the Bay of Islands Complex (Mercier, 1976; Girardeau, 1979; Girardeau and Nicolas, 1981). Girardeau and Nicolas (1981) characterize the lower peridotites as having porphyroclastic textures, equant orthopyroxene and only slightly elongated spinel. They also note strong olivine preferred orientations (see Chapter V).

The enstatite crystals in the lower harzburgites range from 1 to 5 mm (2 mm average). They show no [001] elongation, although quite often they may show slip along the cleavage plane which lies perpendicular to [001] (Figure III-6). Clinopyroxene exsolution lamellae occur in less than 20 percent of the grains. Most often it occurs along the same cleavage trace which is reactivated by slip although

Figure III-5. Index Map of Table Mountain showing the geographic distribution of the petrographic units described in this chapter. The coarse stippling denotes the observed range of transitional harzburgites; the diagonal hachuring indicates the transition zone between the upper and lower harzburgites; horizontal hachuring delineates the zone affected by basal overprinting.

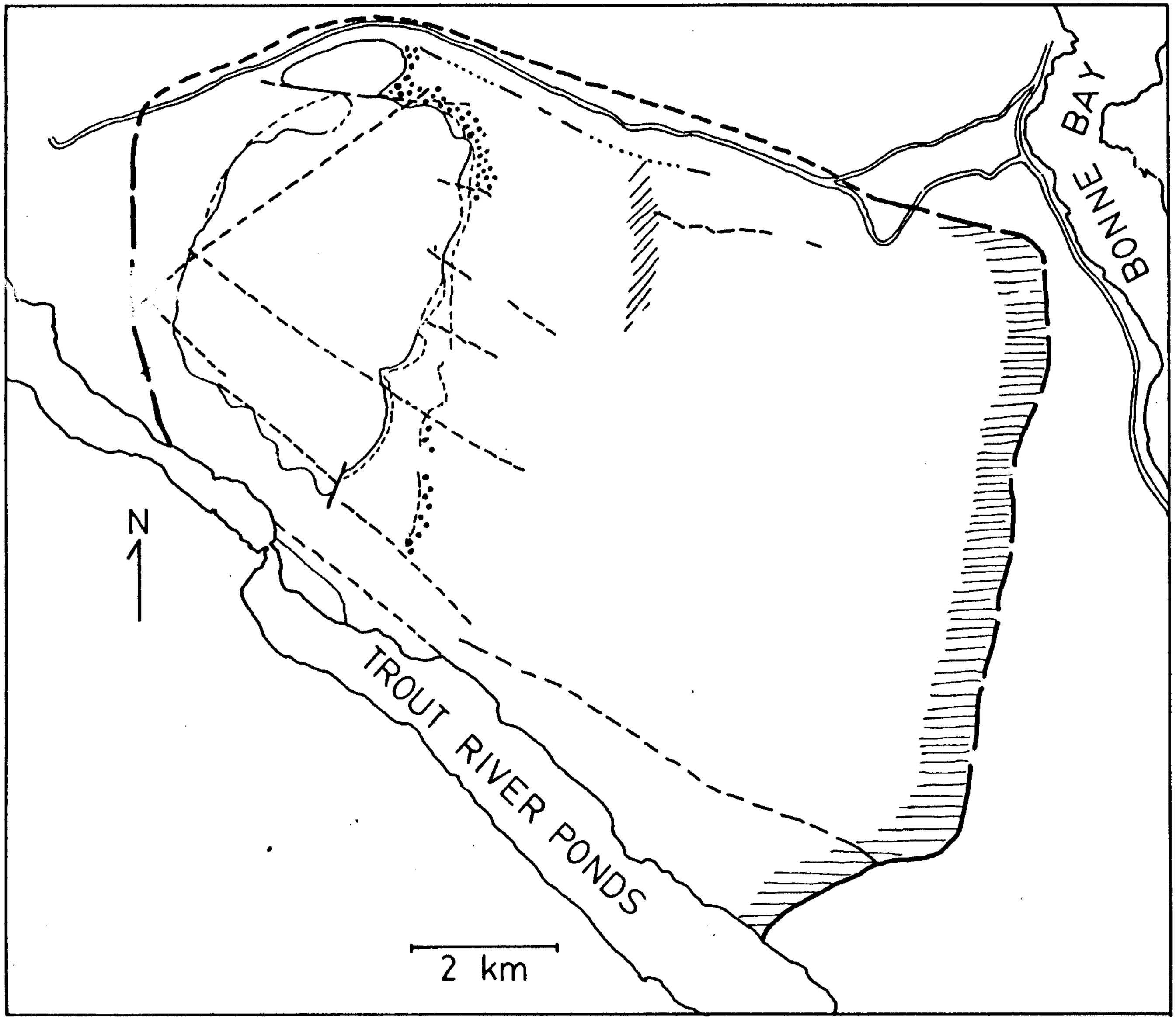

BONNE BAY
N
TROUT RIVER PONDS
2 km

Figure III-6. (A: plane polarized light; B: crossed nicols). Enstatite grain within the lower harzburgite unit. Slip has occurred along the visible cleavage plane which is approximately aligned with the trace of the foliation. Minor clinopyroxene exsolution parallels the cleavage in the lower portion of the crystal. The field of view is just under 1 cm.

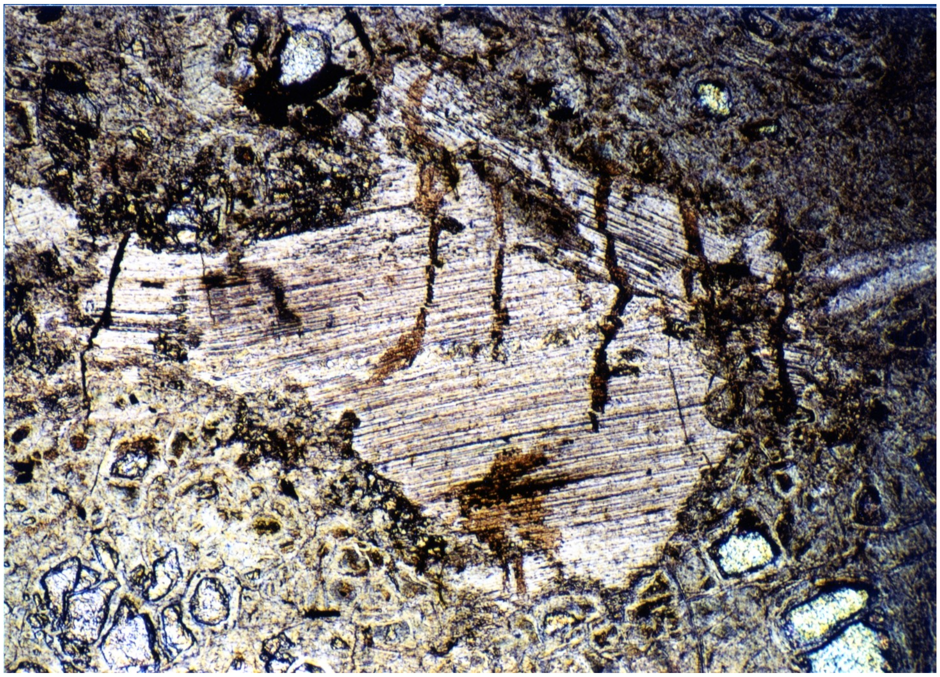


Figure III-6A: View in plane polarized light.

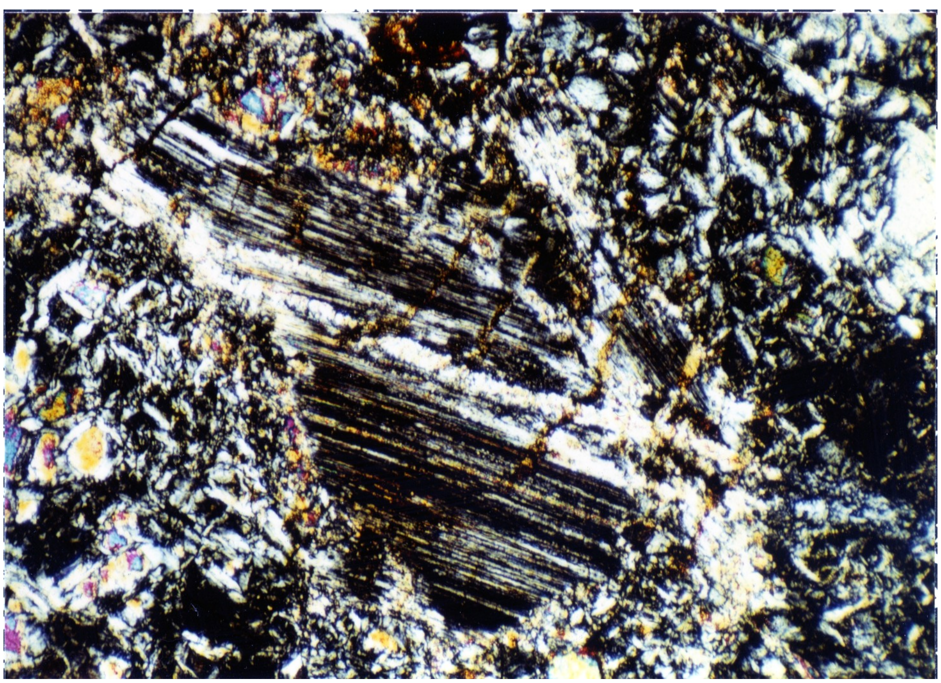


Figure III-6B: View in cross-polarized light (crossed nicols).

Enstatite grain within the the lower harzburgite unit. Slip has occurred along the visible cleavage plane which is aligned with the trace of the foliation. Minor clinopyroxene exsolution parallels the cleavage in the lower portion of the crystal. The field of view is just under 1 cm across.

another set is noted which is highly oblique to this trace. Extensive bastite replacement and pseudomorphing affects nearly all enstatite crystals which are less than 2 mm across. The polycrystalline enstatite clots are an exception to this as bastite is mostly confined to the perimeter of the clots, and along the grain boundaries and fractures. The bastite pseudomorphs have a fibrous fabric which is controlled by the orientation of the $\{110\}_{en}$ cleavage. This fabric shows a moderately developed preferred orientation in thin section.

A majority of the enstatite crystals show evidence of strain. Weak to moderate undulatory extinction is typical. In some enstatite aggregates, this extinction may sweep symmetrically into the grain from an "impact" point along its margin where another crystal is butted up against it (Figure III-3B). This suggests that mechanical deformation has pressed grains within the aggregate against one another. It is interesting to note that the clinopyroxene occurring within these rocks is distinctly less altered than the orthopyroxene.

Spinel also shows different textures in the harzburgite units. Within the lower harzburgites, spinel usually occurs in subhedral grains which range up to 3/4 mm in diameter. The larger crystals are always more or less equant and may show weakly developed octahedral cleavage. The smaller grains (i.e. those less than 1/4 mm) are usually weakly elongated and may often be cuspate.

Within the lower harzburgites, a slight change in olivine fabrics occurs with increasing structural depths. While porphyroclastic textures are displayed by all samples examined, the lowermost samples typically had significantly larger ratios of tabular to equant olivine crystals. In addition, the average size of the equant olivine grains appeared to be smaller in the lower levels.

Lherzolite Interlayered With The Lower Harzburgites

Along the eastern wall of Winter House Brook, wispy patches of clinopyroxene-rich harzburgite and lherzolite are interlayered with the harzburgite (see Chapter IV). These rocks contain 5 to about 10 percent diopside. This clinopyroxene is usually subhedral and is most often associated with enstatite. Otherwise, the rock shows identical textures to the surrounding harzburgite.

CHAPTER IV

MESOSCOPIC STRUCTURAL GEOLOGY

This chapter is organized as a traverse commencing with the structurally highest units of the Table Mountain Massif (the layered gabbros) and continuing down-section to the basal peridotites. Plates A and B summarize the geological mapping conducted by the author. The enlarged cartoons superimposed on Plate B typify the structures addressed in later sections of this chapter. The exposures of the cumulate suite are limited to an approximately flat-lying carapace on the western edge of the massif (Figure IV-1). Residual tectonites comprise the remainder of the massif. As this study concentrated on the deformed cumulates and the harzburgites, the detailed work of other researchers is reviewed for those units not concentrated upon in this study.

Undeformed Layered Gabbros

The uppermost unit of the massif consists of layered and lineated gabbros, hornblende gabbros and olivine gabbros. Both compositional and grain size layering is observed with layers ranging in thickness from 2 mm to several meters. Layering is generally discontinuous along-strike within 50 to 100 meters. O'Connell (1979) describes two groups of structures which she attributes to sedimentary processes active in a magma chamber. The first group includes channels, cross bedding and graded bedding, while the second contains slump features, folds and faults. She notes the difficulty in distinguishing between tectonic and

Figure IV-1: Photo looking westward along the crest of the northern face of Table Mountain. The more resistant grey rocks cropping out in the upper background are the plagioclase-bearing cumulates. The light buff colored patches in the middle background are dunites while all rock in the foreground is harzburgite. The Gulf of St. Lawrence is in the distance.

sedimentary features in metamorphic rocks (i.e. Hobbs, Means and Williams, 1976, pp. 156-159). None the less, she argues for a sedimentary origin for the majority of the structures. Clearly, for reasons discussed below, this is not the case.

Many workers have described distinct undeformed and deformed sections of the cumulate suites recognized in ophiolites (for example, Moores, 1969; Juteau et al, 1977; George, 1978; Dewey and Kidd, 1977). Both kinds of rock are well developed on Table Mountain.

The undeformed cumulates display both groups of sedimentary-appearing features. No penetrative foliation or lineations related to solid-state plastic flow are observed and fold axes (slump folds) are not as consistently oriented as they are throughout the tectonized assemblage. The dominant "S" type fold vergence described by O'Connell (1979) is not shown anywhere on her map, but is associated with the underlying deformed cumulates. Toward the base of the undeformed cumulates, a 10 meter thick section of feldspathic dunites interlayered with the gabbros has been described by Girardeau (1979). The total thickness of this unit on Table Mountain is approximately 300 meters. This is relative to the inferred horizontal surface defined by the gross contact between the cumulate and residual tectonite suites.

Deformed Cumulates

A 220 meter thick suite of deformed cumulates is sandwiched between the layered cumulates and the tectonized ultramafics. The nature of the contact with the overlying cumulates is a gradation over a 10 meter thick zone, but is not well described in the literature. Girardeau (1979,

1981) notes an alternation of olivine gabbros, troctolite, gabbros, feldspathic dunites and uncommon anorthosites within the unit. Feldspathic dunite and troctolite with rare websterite become the dominant lithologies toward the base. Strong penetrative foliation is present on both outcrop and thin section scale. It is defined by the flattening of the tectonically partially active crystals (those which are less ductile than the bulk of the rock yet still undergo deformation). These include the pyroxene paleoblasts, spinel grains and plagioclase. Plagioclase is an excellent marker in the field as it is more resistant to weathering, is light in color, and it appears to have behaved in a very ductile manner, preserving small-scale fold hinges and rodding lineations. Websterites may also serve as marker layers (Figure IV-2).

Considerable strain is evidenced by extensive transposition of primary layering (S_0) along the plane of the foliation (S_1) and well developed lineations (L_1). (Petrofabric data discussed in the next chapter give strong fabrics which further support large strains having affected these rocks). Primary layering is preserved in places with a maximum angular separation of 5 to 10° between layering and foliation. Furthermore, isolated intrafolial isoclinal fold hinges are common. No primary lineations (L_0), i.e. those related to magmatic "sedimentation", are seen. The following lineations have been identified:

Spinel lineation
Rodding lineation (agrregate plagioclase)
Tabular pyroxene lineation

In all cases, these lineations lie within the foliation plane, but they are not always coaxial with one another, having up to a 15 degree angular separation.

Figure IV-2A. Strongly deformed layered cumulate showing intrafolial isoclinal fold hinges and a few "S"-type folds. A harzburgite cobble is in the right foreground.

Figure IV-2B. Plan view of the same outcrop shown in Figure IV-2A. Rodding lineation is distinctly developed and has approximately the same orientation as the fold hinges in the residual harzburgite.

Figure IV-2A: Strongly deformed layered cumulate showing intrafolial isoclinal fold hinges and a few “S”-type folds. A harzburgite cobble is in the right foreground.

Figure IV-2B: Plan view of the same outcrop shown in Figure IV-2A. Rodding lineation is distinctly developed and has approximately the same orientation as the fold hinges in the residual harzburgite.

Little field data on lineations were obtained from the deformed cumulates. Spinel lineations, while present and clearly observed in thin section, are too sparsely developed to be easily identified in the field. Enstatite lineations were not observed, although they may be developed in the websterites. Rodding lineations defined by plagioclase aggregates within troctolite are very common. On the north face of Table Mountain plunges of the lineation range from N90W 30W to N50W 40W (Plate A).

Folding of cumulate layering and early intrusives is very common in this assemblage. The foliation is usually not affected by folding and is axial planar with respect to it. Folds of layering are tight to isoclinal, often intrafolial, with consistent "S" type vergence (Figure IV-2). Fold hinges are uniformly oriented, plunging from N60W 55W to N50W 32W along the northern face of the mountain.

Intrusive veins of orthopyroxenite and feldspathic websterite are observed in a few places. Girardeau (1979) has observed gabbroic dikes as well. These generally show some deformation in the form of open to close folding. No fold vergence data was obtained from these veins and insufficient data has been collected to be able to apply Flinn diagrams to intrusives in this unit.

The contact between the cumulates and the underlying tectonized dunites and harzburgites is nearly flat-lying, dipping no more than 10° to the west along the northern and sourthern slopes of the massif. The western face is crosscut by several faults and the outcrop pattern is significantly offset. The attitude of the layering and foliation are also slightly deflected, indicating that the assemblage is slightly synformal with its axis plunging WSW10. Similar results are obtained by comparing the change in orientation of the foliation in the harzburgites from SW to NE. Casey and Kidd (1981) give evidence that similar structure is observed for the North Arm Massif as well.

Foliated Dunites

Underlying the deformed cumulates are foliated feldspathic dunites (no more than 20 meters thick) and homogeneously foliated dunites (0 to 300 meters thick). The upper contact of this suite is gradational with dunite content increasing fairly rapidly over a 2 to 10 meter interval, although it may be abrupt in places. Unfortunately, few outcrops of this transition are exposed on the northern face, and those along the Trout River Ponds are highly disrupted by later faulting. The lower contact with the tectonized harzburgites is again a gradation over a 10 meter interval with orthopyroxene content increasing downwards within the dunite and thin discontinuous harzburgite layers intercolated within the dunite. Small patches of lherzolite may be located within the transition zone between the dunites and the residual harzburgites. They appear to have a limited extent, reaching a maximum size of approximately 3 by 10 meters on the northern face of Table Mountain. Clinopyroxene is quite fine-grained (~½ mm) and may constitute up to 10% of the rock. Petrographic examination indicates that it generally appears as an "intercumulus" phase lying in small voids between enstatite and olivine crystals. Usually, it appears to be less strained than the other phases.

Similar bodies have been described in other ophiolites (e.g. Trinity, Lindsley-Griffin, 1977; Papua, England and Davies, 1973). Their origin has been attributed to incomplete extraction of partial fusion products (George, 1978 and personal communication).

Possible cumulate xenoliths have also been observed in this zone. A finely layered websterite/dunite block (cobble sized) is completely encased in harzburgite (Figure IV-3A). The boundaries between the block and the harzburgite are extremely sharp (on the scale of the grain size). As no other examples were observed and no evidence of an associated conduit or pod were observed, little can be ascertained from it.

In the field, dunites weather to a rusty brown or tan. They appear to be very fine-grained as serpentinization has riddled the olivine grains, leaving isolated unaltered fragments ranging up to 1 mm across. Fresh surfaces are dark greenish gray to black. The outcrops are often massive and the foliation difficult to define. Chrome spinel defines a lineation and, uncommonly, thin (1 to 2 mm) discontinuous layers of chromite and, more commonly, orthopyroxenes are observed parallel to the foliation. Serpentinization fabrics are also observed. These consist of anastomosing veinlets, approximately ½ mm thick, that occur in apparently discontinuous zones, 10 cm to 1 meter wide and 2 to 5 meters in observed lateral extent. This fabric is usually highly oblique to the foliation but, in some instances, parallels it. In no instances does it offset foliation or show any structures which suggest any significant motion across the zone. Petrographic examination of these dunites (see Chapter III) suggests that intercumulus clinopyroxene

Figure IV-3A. Finely layered websterite/dunite cumulate encased in foliated, transitional harzburgite. The layering in the cobble-sized "xenolith" is parallel to the S_1 foliation in the harzburgite.

Figure IV-3B. Large dunite pod with smaller dunite clots immediately adjacent to it. The country rock is homogeneously foliated harzburgite.

Figure IV-3A: Finely layered websterite/dunite cumulate encased in foliated, transitional harzburgite. The layering in the cobble-sized "xenolith" is parallel to the S_1 foliation in the harzburgite.

Figure IV-3B: Large dunite pod with smaller dunite clots immediately adjacent to it. The country rock is homogeneously foliated harzburgite.

and plagioclase are more abundant (1 to 3%) in the uppermost dunites as well as those adjacent to the lherzolites.

Intrusive bodies are scarce but become more common toward the base of the dunites. Orthopyroxenite veins are the most common, but possible websterite/gabbro and norite dikes also occur. The veins are in almost all cases less than 30 cm thick. Open folding is common along intrusives cutting across the foliation although intrafolial, isoclinal fold hinges are also observed. Again, due to limited exposure, insufficient data was gathered to meaningfully compare dike orientations with extent and nature of deformation. However, the impression from field data is that similarly oriented dikes have experienced variable amounts of deformation. This is examined more extensively in the description of the harzburgites.

Harzburgite Unit

Harzburgites are the dominant lithology exposed on Table Mountain. The tectonized harzburgites of the Bay of Islands Complex and all other ophiolite massifs, and recovered mantle xenoliths, are typified by two characteristics not observed in ultramafic igneous intrusions such as the Skaergaard and Bushveld. These are: 1) non-cumulate compositional layering and 2) penetrative folding and lineations of remarkably consistent orientation. The harzburgite's residual nature has been argued on geochemical and textural grounds by Mercier (1976) and thus will not be addressed here.

Layering is defined by distinct variation in enstatitie/olivine concentrations within the harzburgite. Typical layers range from 1 to 15 cm thick and may contain up to 50 to 80% enstatite. They generally occur in multiple clusters of 3 to 5 closely spaced layers separated by harzburgite (Figure IV-4). Dunite layering is also present, although it is not as common as enstatite layering. It occurs more frequently in the uppermost harzburgites and in the lower peridotites exposed at Winter House Brook. Typically, layers range from 2 to 10 cm in thickness and are often rhythmically alternate with harzburgite layers (Figure IV-4).

Continuous zones of well-defined layering have been documented in some other ophiolites over areas up to 3 or 4 km^2 (Dick and Sinton, 1979; Boudier and Coleman, 1981). More commonly, layering is reported to consitute 20 to 30% of individual outcrops and is not laterally continuous for more than a few tens of meters (George, 1978; Moores, 1969).

Within the harzburgite suite on Table Mountain, three groups of structures may be distinguished.

Dunite pods (Figure IV-3): These occur throughout the massif but are most common in the uppermost harzburgites. They range in size from approximately 20 cm to 3 to 5 meters across. The contact between dunite and harzburgite is generally quite sharp, occurring within 5 cm. The contact is sharper along surfaces which are approximately parallel to the foliation, often within 1 to 3 cm. The shape of these bodies is elliptical to lobate (long axis is parallel to foliation). The dunites are massive in outcrop, but foliation within them is often evidenced by sparse enstatite and spinel trails.

Layering of limited extent (< 15 meters in lateral extent): This is observed throughout the harzburgite suite. It is often associated with remnants of intrusive dunite bodies which clearly crosscut the harzburgites. No direct association was observed between the enstatite layering and pyroxene intrusives although boudins of orthopyroxenite with their long axes within the plane of foliation are common (Figure IV-4 and cartoons Plate B). Enstatite-rich layers are quite variable in thickness, ranging from 1 to 20 cm, while dunite layers range from 1 to approximately 15 cm. The attitude of the layering usually parallels the foliation, but may be very slightly oblique to it (up to 5°). The foliation does penetrate the layering. The nature of the contact between the layers and the surrounding harzburgite seems to depend upon the composition of the layers. Orthopyroxenite layers commonly have sharper contacts than the dunite layers.

Continuous, rhythmic layering: This type of layering is best exposed along the northern face of Table Mountain in the upper half of the harzburgite assemblage. It may very well occur throughout the peridotites, but the nature of the exposures limited extent along the layering from the cirque immediately west of Winter House Brook eastward made verification impossible. This form of layering is defined by distinct groups of enstatite-rich layers, 10 to 100 meters in thickness, that are traceable as a whole for nearly two kilometers. Individual layers may range from 2 to 10 cm in thickness and were not traced over this distance (It is doubtful that they are as continuous) as exposure and relief prohibited this detailed an examination. The pattern of clusters of layers separated from one another by homogeneous, foliated harzburgite was traced on an outcrop scale up the northern face of the massif (see Plate A).

The individual enstatite-rich layers may display homogeneous grain size and concentration (i.e. are isomodal) or may have coarser-grained, more pyroxene-rich centers. A few examples of zoned layering are observed although it is unclear if these had an intrusive origin. They are described later. The boundaries of the layers are quite sharp (less than 1 cm) although, uncommonly, gradation in proportion and/or grain size may be noted. At outcrop scale, a continuous transition between massive foliated harzburgite and rhythmically layered harzburgite is often observed. This is best illustrated with an annotated series of photographs (Figure IV-4). Layering which is continuous for 10 meters or more is always observed to be parallel to the foliation.

Figure IV-4. Annotated series of photographs depicting the transition from foliated harzburgite with a massive appearance to large-scale layering.

A: Foliated harzburgite with very weakly aligned enstatite crystals. The trace of the foliation plane dips slightly to the left in the photo. Also note the centimeter sized polycrystalline enstatite clots.

B: Distinctive tabular enstatite lineation. The face of the outcrop approximately parallels the foliation plane. It is just possible to observe very fine spinel trails defining a lineation which is approximately parallel to the enstatite aggregates.

C: Strongly foliated harzburgite. No layering is developed in this outcrop. Instead, the foliation has slightly concentrated the enstatite in irregular, one to three grain thick zones.

D: Very fine-scale compositional layering. The foliation is parallel to the enstatite layers. The crosscutting features are late-stage serpentinite veins and are not penetrative features on outcrop scale.

E: Fine-scale dunite layering within foliated harzburgite. Again, the foliation is parallel to the layering.

F: Diffuse enstatite layering. The harzburgite between layers is foliated but has a nearly homogeneous appearance.

G/H: Large-scale enstatite layering. Note the clusters of enstatite layers separated by foliated harzburgite.

Figure IV-4A: Foliated harzburgite with very weakly aligned enstatite crystals. The trace of the foliation plane dips slightly to the left in the photo. Also note the centimeter sized polycrystalline enstatite clots.

Figure IV-4B: Distinctive tabular enstatite lineation. The face of the outcrop approximately parallels the foliation plane. It is just possible to observe very fine spinel trails defining a lineation which is approximately parallel to the enstatite aggregates.

Figure IV-4C: Strongly foliated harzburgite. No layering is developed in this outcrop. Instead, the foliation has slightly concentrated the enstatite in irregular, one to three grain thick zones.

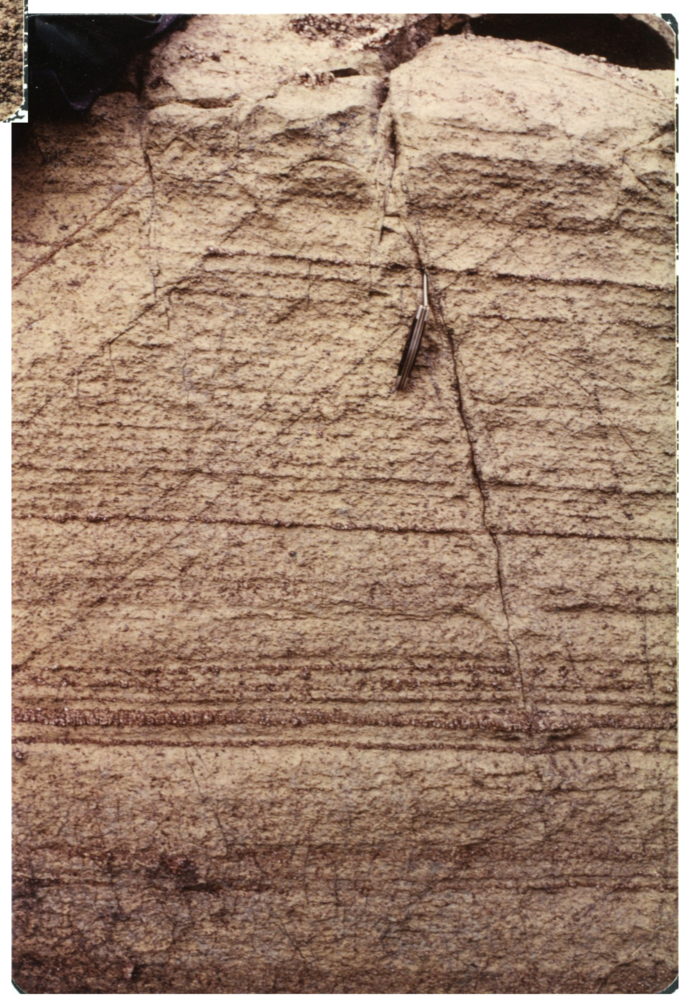


Figure IV-4D: Very fine-scale compositional layering. The foliation is parallel to the enstatite layers. The crosscutting features are late-stage serpentinite veins and are not penetrative features on outcrop scale.

Figure IV-4E: Fine-scale dunite layering within foliated harzburgite. Again, the foliation is parallel to the layering.

Figure IV-4F: Diffuse enstatite layering. The harzburgite between layers is foliated but has a nearly homogeneous appearance.

Figure IV-4G: Large-scale enstatite layering. Note the clusters of enstatite layers separated by foliated harzburgite.

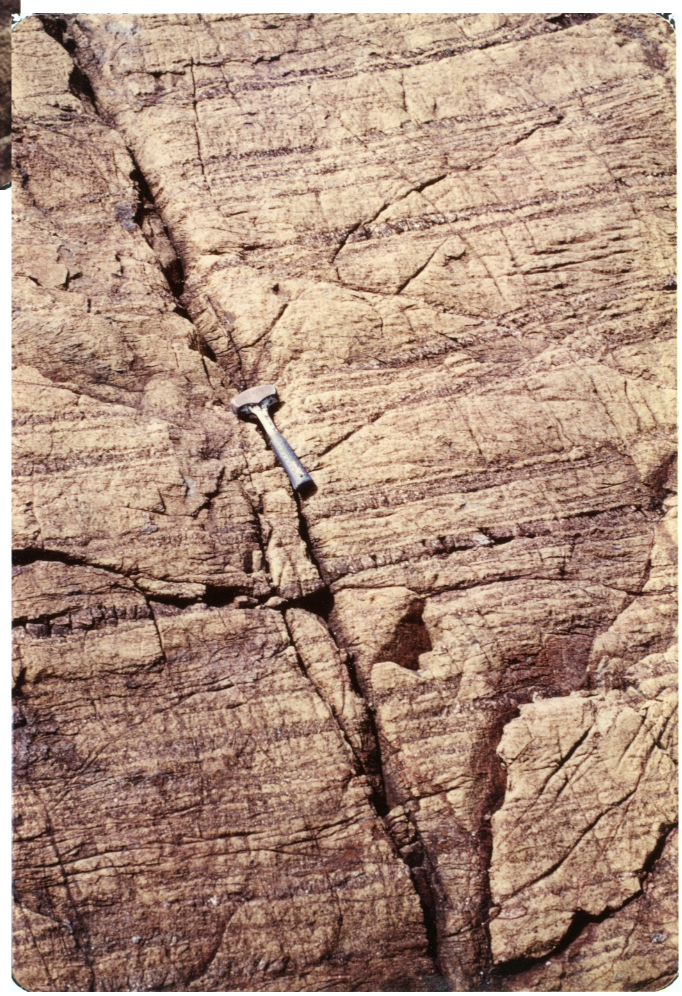


Figure IV-4H: Large-scale enstatite layering. Note the clusters of enstatite layers separated by foliated harzburgite.

Figure IV-4I: Large-scale dunite layering within the lower harzburgites. This layering was continuous through several outcrops along-strike (approximately 100 meters). Note the apparent pinch and swell structure of the thin orthopyroxenite layers in the lower part of the photograph (dark layers).

A gradational relationship exists between intrusive bodies (including the pods) and the layering of limited extent. Clear evidence of transposition of early intrusives includes boudinage of orthopyroxenites, isoclinal folding of both enstatite and dunite veins, often resulting in isolation or truncation of fold hinges and, in some cases, segmentation and rotation of fragments of the intrusive body along the plane of the foliation. However, transposition cannot easily be involved as a mechanism responsible for the formation of the rhythmic and continuous layering.

Dick and Sinton (1979) reviewed the proposed mechanisms capable of generating the layering. These include magmatic differentiation (gravitational settling), mechanical segregation (flow differentiation) and metamorphic differentiation. A magmatic origin was rejected by Dick and Sinton because of the compelling geochemical data which suggest that upper mantle harzburgites are depleted (i.e. residual) as a result of partial fusion. Also, the layering observed in tectonized harzburgites displays none of the structures commonly attributed to magmatic sedimentation (e.g. channels, cross bedding and graded bedding) or those attributed to _in situ_ nucleation (comb structure).

They did not completely reject flow differentiation. This mechanism requires that the system contain at least two phases which display different mechanical behavior under differential stress and the presence of shear gradients. Dick and Sinton argue that olivine flow is controlled by power law creep and that the difference in competencies of olivine and enstatite were far less than the phases with which Bhattacharji (1967) demonstrated flow differentiation. Dick and Sinton further note that the penetrative deformation of a plastic solid often produces alternating high and low strain regions. These observations agree well with the field data collected on the layering of limited extent. Therefore, the transposition of early intrusive bodies in the harzburgite likely involves mechanical segregation resulting from plastic flow.

Dick and Sinton conclude that metamorphic differentiation, differential solution accompanying deformation and ongoing anatexis contribute to form the compositional layering. Their mechanism requires the development of alternating high strain (olivine-rich harzburgite or dunite) and low strain (enstatite-rich) zones. Pressure solution in the presence of a small amount of melt is the principal deformation mechanism proposed. This is in contradiction of the observations of strong olivine fabrics which TEM studies indicate formed as a result of solid-state deformation in a rotational regime with a dominant [100] (010) slip system. (Nicolas and Poirier, 1976) One explanation may lie in strain-induced preferential dissolution. Bosworth (1981) proposed that dissolution of crystalline material with high defect (dislocation line) concentrations is more rapid than that of unstrained crystalline material.

Foliation and Lineations in the Harzburgites

The oldest penetrative foliation (S_1) observed within the massif is defined by flattened enstatite crystals and aggregates. Often, this grades into a weakly defined on grain thick layering (Figure IV-4). Within dunites, the trace of the foliation plane may be indicated by aligned chromite/spinel grains and/or sparse, streaked-out enstatite aggregates. Rarely, a slight flattening of olivine crystals may be observed in thin section. Due to extensive serpentinization, this is impossible to detect in the field. It is important to note that a later serpentinization fabric has been identified. Usually it is highly oblique to S_1 and may alter grains in such a manner as to indicate elongations unrelated to the primary fabric (Figure IV-4).

The foliation penetrates the compositional layering. In all cases where layering is laterally continuous for more than 10 to 15 meters, it exactly parallels the foliation. Foliation does crosscut the deformed intrusives.

On map scale, the foliation clearly fans. In the uppermost harzburgites, the average orientation is N25E 30-40W. At approximately 1.5 km down-section from the deformed dunites, the dip of S_1 appears to increase abruptly to approximately 60W. This change is poorly recorded on the traverse shown in Plate A but is apparent in Girardeau's map (1979). Further down-section a progressive change in attitude from N25E 30W to N40-45E 25W occurs, with the latter attitude typical of the basal harzburgite. This progressive change in orientation appears to be independent of the open synformal structure of Table Mountain.

All observed lineations lie within the plane of foliation. Darot and Boudier (1975) identified five lineations commonly observed in peridotites. These are the following:

Tabular enstatite lineation (Figure IV-4B): large (0.5 to 1.5 mm) aligned tabular enstatite grains, often grouped in clusters. The grains have an elliptical shape within the foliation plane and have cleavage traces approximately perpendicular to the elongation of the olivine crystals.

Lamellar enstatite lineation: elongated lamellar enstatite crystals lying flat within the foliation plane (length to width ratio between 8 and 15). The $[100]_{en}$ cleavage trace is perpendicular to the grain's elongation. This texture is common in recrystallized mylonites.

Aggregate enstatite lineation: enstatite porphyroclasts are surrounded by fine recrystallized enstatite in the foliation plane. This texture is observed in deformed lherzolite xenoliths recovered from kimberlites.

Spinel lineation: this is defined by linear trails of spinel grains occurring either as elongated crystals or small equant grains within the foliation plane. Uncommonly, spinel exsolution textures occur within tabular enstatite crystals and may define a second lineation. (These are seen in the Table Mountain suite, but no fabric data on them is available.)

Aggregate spinel-plagioclase lineation: within plagioclase lherzolite, lenses of plagioclase rimming spinel define the lineation.

Within the harzburgite assemblage of Table Mountain, tabular enstatite, both forms of spinel and possibly an aggregate enstatite lineation are recognized. It is quite difficult to accurately define the orientations of the tabular enstatite lineation in the field. The principal reason for this is a conspicuous lack, in most outcrops, of exposed surfaces parallel to the foliation. Even so, the lineation is not particularly distinct. While the enstatite grains are very tabular, they are coarser than the norm of Darot and Boudier, typically ranging from 2 to 5 mm (they may reach 1+ cm in the lower harzburgite). The aggregates are mildly elongated but often the long axes of the clusters on a given face give a scattered result (Figure IV-4). The best method for determining the orientation of the lineation is to examine oriented slabs with the cut face parallel to the foliation. Thin sections may also be used but these are of too limited an areal extent to give reliable results.

In contrast to this, the spinel lineations are always extremely distinct. The spinel grains are fine-grained (less than 1.5 mm) and sparse (1 to 3 modal percent). Their disseminated nature makes field determinations difficult without good three dimensional exposure.

Girardeau's lineation measurements from Table Mountain have been synthesized into form lines and superimposed on a generalized geologic map of the massif (Figure IV-5). While the author has not made laboratory determinations of the lineations, field data (Plate A) is in agreement with Girardeau's results. It is important to recognize that field determinations are much more variable than lab and thin section data due to ambiguous exposure in the field.

Upon close examination, Girardeau's map indicates that the spinel lineation within the upper 1.5 kilometers of the harzburgites have, on average, a 10 degree steeper plunge. Throughout the remainder of the harzburgite suite, the plunge remains approximately the same but the bearing fans in conjunction with the foliation. Finally, a significant disruption of the systematic orientation of the spinel lineation occurs in the basal harzburgites and lherzolite.

On the basis of these moderately defined changes, the harzburgites may be separated into three zones. These have been superimposed on Figure IV-5.

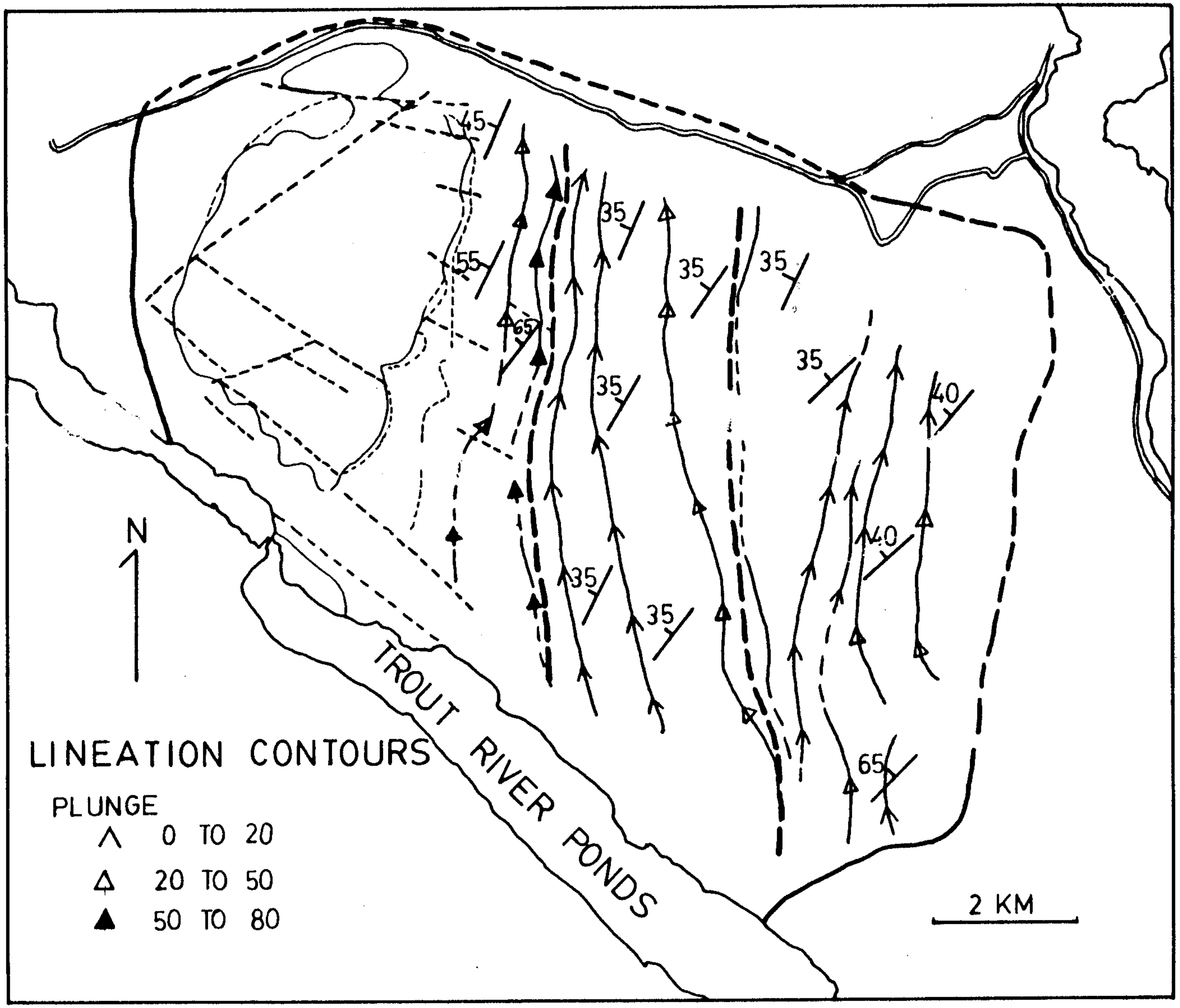
Basal Overprinting

The lowermost zone has a more disjointed structure than the remainder of the massif. The structures have been interpreted as resulting from a very strong deformation superimposed on the S_1 foliation. The zone has a total thickness of about 1000 meters (Girardeau and Nicolas, 1981).

Intrusive Bodies

The intrusives most commonly observed crosscutting the harzburgites are orthopyroxenites and dunites. Websterites and gabbro-norites are very rarely seen and only in the uppermost sections. Dunite intrusives (including pods) are most common within the upper 1.5 km and in the

Figure IV-5. Generalized geologic map of Table Mountain showing lineation form lines synthesized from Girardeau's (1979) data and this thesis. Heavy dashed lines separate three zones which have systematic internal changes in the orientation of structural elements.


LINEATION CONTOURS
PLUNGE
0 TO 20
20 TO 50
50 TO 80
TROUT RIVER PONDS
2 KM
N
45
55
65
35
35
35
35
35
35
35
40
40
65

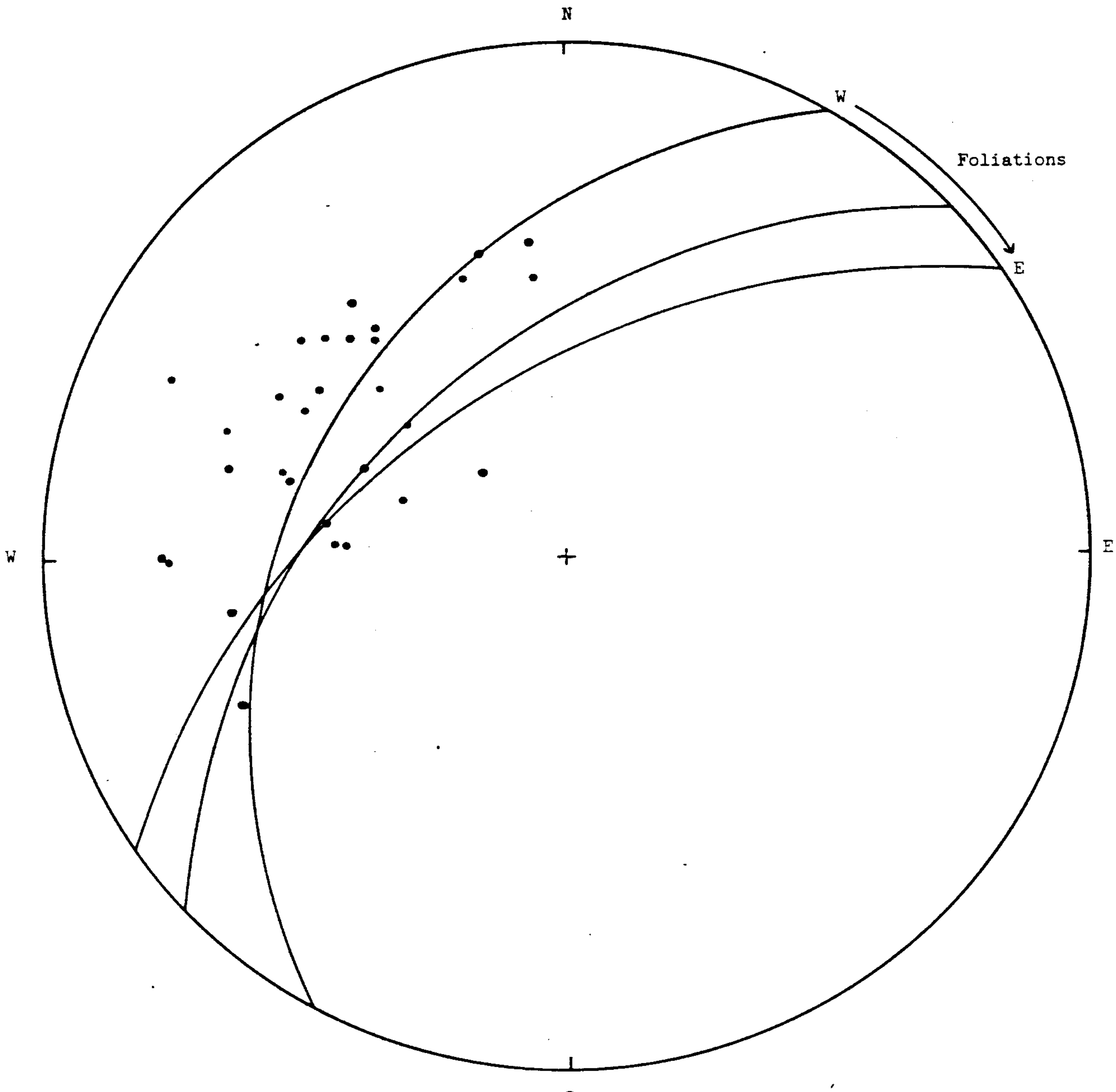


Diagram depicts fold axis determinations plotted with the observed spread of foliation (Lower hemisphere projection)

2 km of the harzburgites, although they are present throughout the massif. No significant variation in frequency of orthopyroxenite veins/dikes is seen throughout the peridotites. Typically, intrusives may constitute up to 1 percent of an outcrop although locally this may be quite variable.

The dikes and veins display widely variable orientations and amounts of deformation. Many bodies of similar orientation show vastly differing intensities of folding and shear parallel to the foliation. In his study of the Lewis Hills Massif, Karson (1977) constructed diagrams modeling pure shear and simple shear of variably oriented tabular bodies (after Flinn). The simple shear mechanism better duplicated the observed structures of the deformed dikes on Lewis Hills. Data collected in this study did not enable me to meaningfully apply this method.

On Table Mountain, intrusives may be arbitrarily separated into two groups, those highly oblique to foliation (45 degrees or more) and those only slightly oblique to foliation (less than 45 degrees). On occasion, intrusives were observed parallel to the foliation. This could never be demonstrated over any significant area, and quite often strong evidence of transposition or ductile shear was noted.

Those intrusives highly oblique to the S_1 foliation are typically folded. The deformational style varies from single open to tight folds, in places with parasitic folds on the larger scale limbs, to multiple symmetric open folds. The composition of the intrusives also appears to control their deformational structures. Similarly oriented dunite and orthopyroxenite bodies which display approximately the same intensity of deformation show markedly different ductility and cohesiveness. Dunites may often be convolute and show much interfingering with the surrounding harzburgite (Figure IV-6). On the other hand, orthopyroxenite bodies always have distinct contacts with the harzburgite and show more brittle features such as boudinage and fractured fold hinges. A few dikes crosscut the foliation and show no evidence of deformation along their traceable extent (100 to 200 meters).

The group of dikes and veins that are slightly oblique to the foliation show largely the same structures that are typical of the highly oblique group. On the average, however, the folds are less abundant, although the amplitude and wavelength of the individual folds is about the same as in the group of highly oblique layers. Orthopyroxenites more commonly show boudinage and pinch and swell structures, while the dunites may have a slightly lesser average thickness than their counterparts in the previous group.

The folds developed in both groups are of the same style and orientation. The S_1 foliation is nearly always axial planar to the folds and the hinge lines show a remarkable consistent orientation throughout the tectonized suite (Plate A and Figure IV-7). The exceptions to this are rare instances where the foliation (S_1) has itself been folded.

Particular attention was given to fold vergence. In the upper 1.5 to 2 kilometers (structural thickness measured perpendicular to contact between cumulate and residual assemblages) of the harzburgites, "S" type vergence was observed looking down plunge. The same vergence and orientation of hinge lines is present in the deformed cumulate

Figure IV-6A. Dunite dike or conduit crosscutting the harzburgite at a high angle to the foliation. The extensive interfingering of the harzburgite and dunite along planes parallel to the foliation would suggest transposition or fabric controlled assimilation.

Figure IV-6B. Orthopyroxenite vein crosscutting the harzburgite at a high angle to the foliation. The vein is slightly deformed (gentle "S" type fold). Note the relatively sharp contacts.

Figure IV-6C. Orthopyroxenite vein crosscutting the S_1 foliation within the harzburgite shows distinctive pinch and swell boudinage.

Figure IV-6D. Thin orthopyroxenite vein which shows evidence of transposition and segregation of enstatite (dark brown stumpy phase) and olivine (creamy gold).

Figure IV-6A: Dunite dike or conduit crosscutting the harzburgite at a high angle to the foliation. The extensive interfingering of the harzburgite and dunite along planes parallel to the foliation would suggest transposition or fabric controlled assimilation.

Figure IV-6B: Orthopyroxenite vein crosscutting the harzburgite at a high angle to the foliation. The vein is slightly deformed (gentle "S" type fold). Note the relatively sharp contacts.

Figure IV-6C: Orthopyroxenite vein crosscutting the S_1 foliation within the harzburgite shows distinctive pinch and swell boudinage.

Figure IV-6D: Thin orthopyroxenite vein which shows evidence of transposition and segregation of enstatite (dark brown stumpy phase) and olivine (creamy gold).

Figures IV-7A and B. Folds of dunite bodies showing consistent "S" type vergence. The folded hinges show consistent orientation (Plate A).

Figure IV-7A: Folds of dunite bodies showing consistent "S" type vergence. The folded hinges show consistent orientation (see Plate A).

Figure IV-7B: Folds of dunite bodies showing consistent "S" type vergence. The folded hinges show consistent orientation (see Plate A).

suite. Further down-section in the harzburgites is a 2 kilometer thick zone, principally exposed along the northern face of the massif, in which only two _in situ_ vergence determinations were made by the author. Significantly, they are within close proximity of one another and gave "Z" type vergence. Girardeau (1979) attempted to separate the harzburgites into three units on the basis of 47 relative sense of shear determinations. The boundary separating his upper and middle zones corresponds exactly with the stream cut where the two "Z" type vergences occur (Plate A). Down section, along the western and eastern walls of Winter House Brook, distinct and consistent "S" type vergences occur. This would indicate a relative sense of shear comparable to that observed in the deformed cumulates and upper harzburgites. Girardeau's map, however, includes the entire Winter House Brook area in the middle zone which he claims experienced sinistral shear (he indicated a dextral sense of shear for the deformed cumulates/upper harzburgites). A more complete discussion of the inferred sense of shear within the massif is given in the following chapter in conjunction with a description of olivine fabric data.

The fact that most folds display similarly oriented "S" type vergence suggests that they formed as a result of a simple shear deformation. The variability of deformation recorded by dikes of similar orientation indicates that simple show was occurring throughout the period the dikes were injected.

Zoned Intrusives

Zoned dikes and veins display a variety of forms on Table Mountain. Within the harzburgite suite they may have orthopyroxenite walls and dunite cores, dunite walls and orthopyroxenite cores, or orthopyroxenite walls and clinopyroxenite/websterite cores (Figure IV-8). Their thickness varies from 3 to 25 cm and they are volumetrically insignificant, constituting less than about 5 to 10 percent of the intrusives. Those dikes which are highly oblique to the foliation almost always have orthopyroxenite walls, while those at a low angle to the foliation (less than 20 degrees) usually have dunite walls (Figure IV-8C).

Casey (1980) described some compositionally zoned dikes which crosscut the basal cumulate suite on North Arm Mountain. Some of these display comb structure, suggesting that crystal growth occurred while melt was flowing through the conduit. Some of the intrusives on Table Mountain display similar structures although they are generally more poorly developed (for example, Figure IV-8B). The intrusives which occur at a low angle to the foliation show different structures. Typically, dunite walled bodies have irregular and often gradational contacts with the harzburgite. The orthopyroxenite cores are often transposed (for example, Figure IV-8C) or may show pull-apart structure. These structures and textures argue for mechanical segregation processes being largely involved in the formation of the zoning. The rare development of comb structure and finer-grained cores is most easily accomplished by continuing flow along a conduit in which crystallization is proceeding from the walls inward. The two proposed mechanisms are

Figure IV-8. Zoned Intrusives.

IV-8A. This vein crosscuts S_1 at a high angle. The margin is a coarse-grained orthopyroxenite of highly variable thickness. The core is dunite with frequent orthopyroxenite clots. Note apparent flame structure just right of the pencil.

IV-8B. This pyroxenite vein crosscuts S_1 at a low angle. The walls are composed of very coarse enstatite - up to 2 or 3 cm, while the core appears to be finer grained - 1-3 mm. - clinopyroxene.

IV-8C. This dunite intrusive appears to have left a trail of harzburgite along its core. It was impossible to ascertain whether the harzburgite was residual (country rock) or primary.

IV-8D. Thin zoned enstatite and dunite vein are lying parallel to S_1.

Figure IV-8A: Zoned intrusives. This vein crosscuts S_1 at a high angle. The margin is a coarse-grained orthopyroxenite of highly variable thickness. The core is dunite with frequent orthopyroxenite clots. Note apparent flame structure just right of pencil.

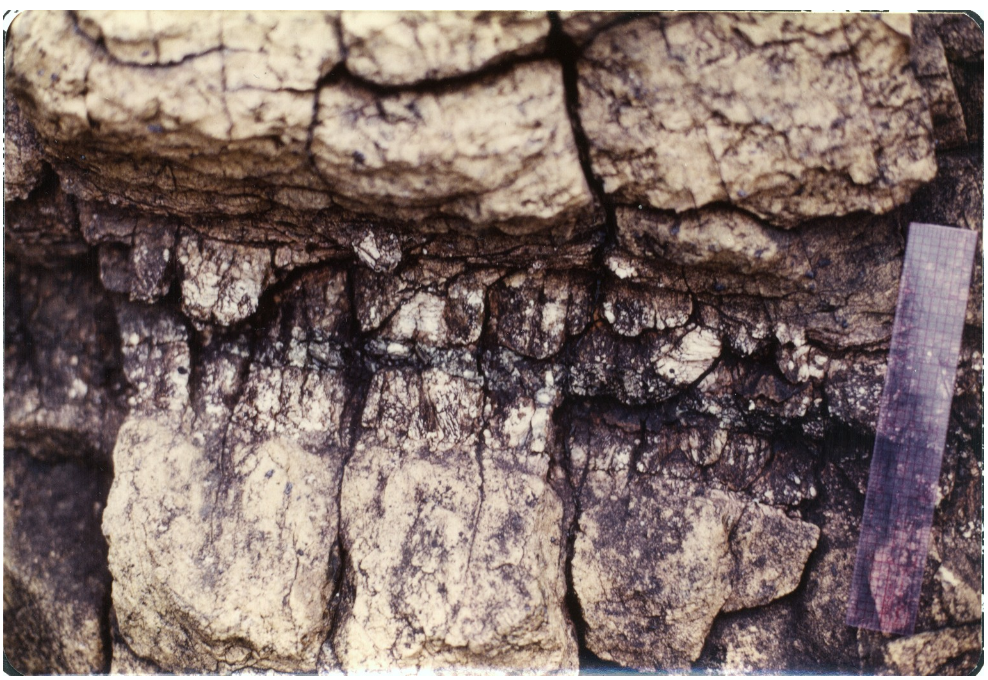


Figure IV-8B: Zoned intrusives. This pyroxenite vein crosscuts S_1 at a low angle. The walls are composed of very coarse enstatite – up to 2 or 3 cm, while the core appears to be finer grained – 1-3mm. – clinopyroxene.

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Figure IV-8D: Zoned intrusives. Thin zoned enstatite and dunite vein are lying parallel to S_1.

not mutually exclusive and, in fact, may occur simultaneously.

A final type of intrusive deserves mention. It was found only once along the eastern wall of Winter House Brook. The dike is approximately 1/2 to 3/4 meter thick and is slightly oblique to the foliation. It contains very large megacrysts of enstatite, ranging up to 10 by 3 cm, which are imbedded in dunite. The enstatites are clearly kinked and show moderate alignment parallel to the dike axis. Chromite clots, up to 1 cm across, are also present and define a very weak planar surface approximately parallel to the dike. Figure IV-9A shows the typical texture of the intrusive. The body can be traced along-strike for several hundred meters.

Recent observations of tabular dunite bodies exposed in the upper harzburgites of the Trinity Ophiolite have suggested that the bodies represent residual material left behind by the upward migration of a picritic melt (Quick, in press). George (personal communication) has suggested that these conduits accumulate refactory phases and that the flux of material determines the composition of the remaining material (i.e. dunitic or orthopyroxene-rich). The term "intrusive" therefore carries the wrong implication for the formation of these bodies.

Irregularly Interlayered Lherzolites

Along the eastern wall of Winter House Brook Valley, small discontinuous wispy patches of lherzolite and clinopyroxene-rich harzburgite are interlayered with the harzburgite. The rock is strongly, but

Figure IV-9. Evidence of metasomatism within crosscutting intrusives.

IV-9A. This dike has a texture which was only observed once on Table Mountain. The clots of enstatite (stumpy brown bronze patches) are aligned with the walls of the intrusive. Note the decrease in enstatite grain size toward the upper wall.

IV-9B. Dunite "web structure" extending into the harzburgite host rock on each side of an orthopyroxenite vein.

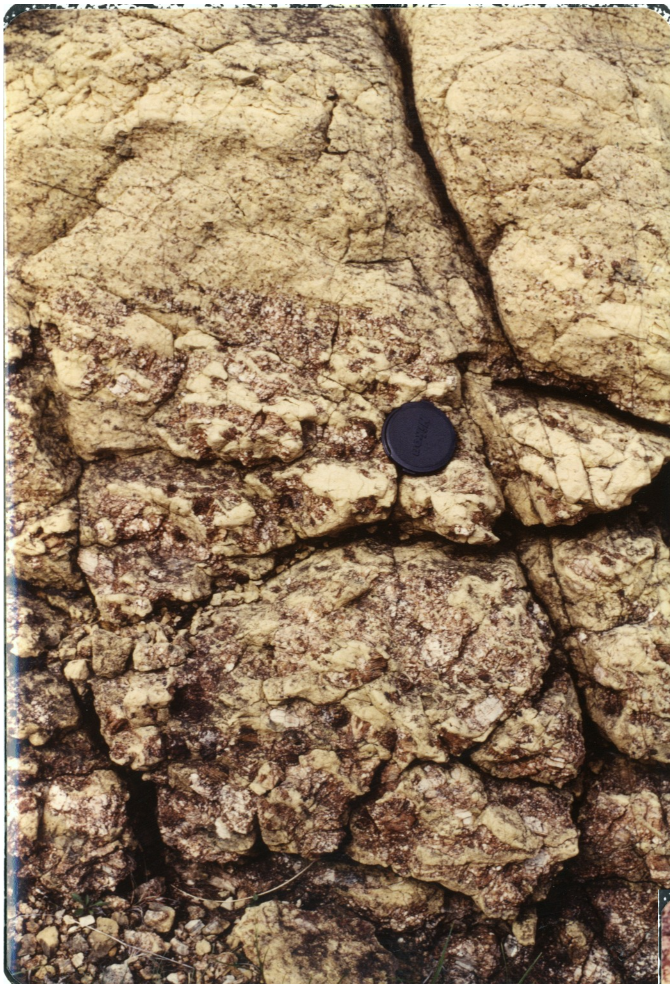

Figure IV-9A: Evidence of metasomatism within crosscutting intrusives. This dike has a texture which was only observed once on Table Mountain. The clots of enstatite (stumpy brown bronze patches) are aligned with the walls of the intrusive. Note the decrease in enstatite grain size toward the upper wall.

Figure IV-9B: Evidence of metasomatism within crosscutting intrusives. Dunite “web structure” extending into the harzburgite host rock on each side of an orthopyroxenite vein.

homogeneously foliated and no change in intensity of deformation is observed throughout the immediately surrounding harzburgite or within the individual patches themselves. These bodies usually range up to 1/2 meter in thickness and may be traceable for up to 3 meters laterally. Their contacts with the harzburgite are gradational over 3 to 20 cm and, notably, they are not significantly sharper along the surfaces most closely paralleling the foliation. The volumetric significance of this lherzolite could not be determined; however, they were not observed elsewhere on the massif. No evidence of ductile or cataclastic shear zones was observed in conjunction with these bodies. Convolute dunite intrusives crosscut the foliation in the surrounding harzburgite but were never seen in association with the lherzolite. The zone in which these lherzolites occur is poorly defined but may be limited to a 200 to 400 meter thick section 7 to 7¼ kilometers down-section from the deformed dunites.

Girardeau and Nicolas (1981) mention the occurrence of these lherzolites and suggest that they might have a cumulate origin. The structural observations cast some doubt upon this. Bender (personal communication) briefly examined the author's thin sections collected from these bodies. He noted that similar textures may be observed in deformed cumulates and that textural criteria are incapable of distinguishing between a refactory or cumulate origin for these rocks. The clinopyroxene is fine-grained (approximately ½ mm) and often associated with enstatite grains, although it may also be found within olivine crystals or in small polycrystalline clots. Undulatory extinction and bent cleavage are as commonly developed in the clinopyroxene as they are in the enstatites. This suggests that the intensity of the deformation experienced by both phases is approximately the same.

Dick (1977) examined the mineral compositions of the primary phases within the Josephine Peridotite of northwestern California and southwestern Oregon. He reported limited systematic variations in composition (Fe, Ca, Al depletion and Mg enrichment) from pyroxene-rich to more refactory pyroxene-poor samples. The observed enstatite compositions ($Wo_0En_{94}Fs_6$) differ greatly from those observed in layered intrusions. Dick argued that clinopyroxene was not present as a separate phase during the late stages of melting and therefore the minor amounts of clinopyroxene observed in the peridotite must have precipitated from trapped melt at the end of fusion. He further noted that a limited variation in partial fusion and melt removal was evidenced by the mineral chemistry.

The chemical, textural and structural observations are most easily explained by the relatively early solidification of clinopyroxene from the trapped melt. It is impossible to establish the timing of the solidification with respect to the deformation. Dynamic arguments suggest that deformation was ongoing during partial melting and continued after crystallization and/or migration of the melt. Another explanation for these lherzolites could be the transposition of large clinopyroxene-rich intrusions early on in the formation of the upper mantle. The limited extent of occurrence of the lherzolite, however, would favor the trapped melt origin.

Ductile Shear Zones

Clear evidence for the formation of ductile shear zones which truncate the foliation and the compositional layering is first observed 2½ km down-section within the harzburgites. Only four of these zones were recognized, with three lying within or eastward of the Winter House Brook Valley (Figure IV-12).

One shear zone has a maximum observed thickness of approximately 5 meters, the others are smaller. Typically, these structures display tight to isoclinal folding of layering and foliation. In two of these, a thin dunite layer defines the hinge plane of the folded foliation (Figures IV-10A and IV-10B). At outcrop scale these dunites appear to have similar textures, grain size and contacts with the surrounding harzburgites to neighboring dunite intrusives. One distinction is the thin, extremely planar nature of the dunites truncating the shear zone. It is possible that these formed as mylonites or at least as the result of large strains leading to mechanical segregation. Further study is required to resolve their origin.

The lateral extent of these shear zones was obscured by limited exposure. In two cases the buckling of the foliation trended directly into the rock face (e.g. Figure IV-10A). The top of one of these buckles is possibly preserved as a tight antiformal structure just south of the head of Winter House Brook. This has a lateral extent of at least 2 km and is about 20 meters across. The hinge line trends approximately N60E; the dip is shallow but unknown. No significant

Figure IV-10. Ductile Shear Zones.

IV-10A. Buckling of the S_1 foliation and compositional layering. Below the hammer S_1 is planar and has an orientation which is consistent with the average for the area. Above the hammer an irregular warp with an amplitude of 2-3 meters is outlined by fine orthopyroxenite layers.

IV-10B. Small scale fold affecting the S_1 foliation. The dunite seam truncates the hinge line.

IV-10C. Small kink fold which disrupts both the enstatite layers and the S_1 foliation which lies parallel to them. Note thick dunite layer at the very top of the photo.

Figure IV-10A: Ductile shear zones. Buckling of the S_1 foliation and compositional layering. Below the hammer S_1 is planar and has an orientation which is consistent with the average for the area. Above the hammer an irregular warp with an amplitude of 2-3 meters is outlined by fine orthopyroxenite layers.

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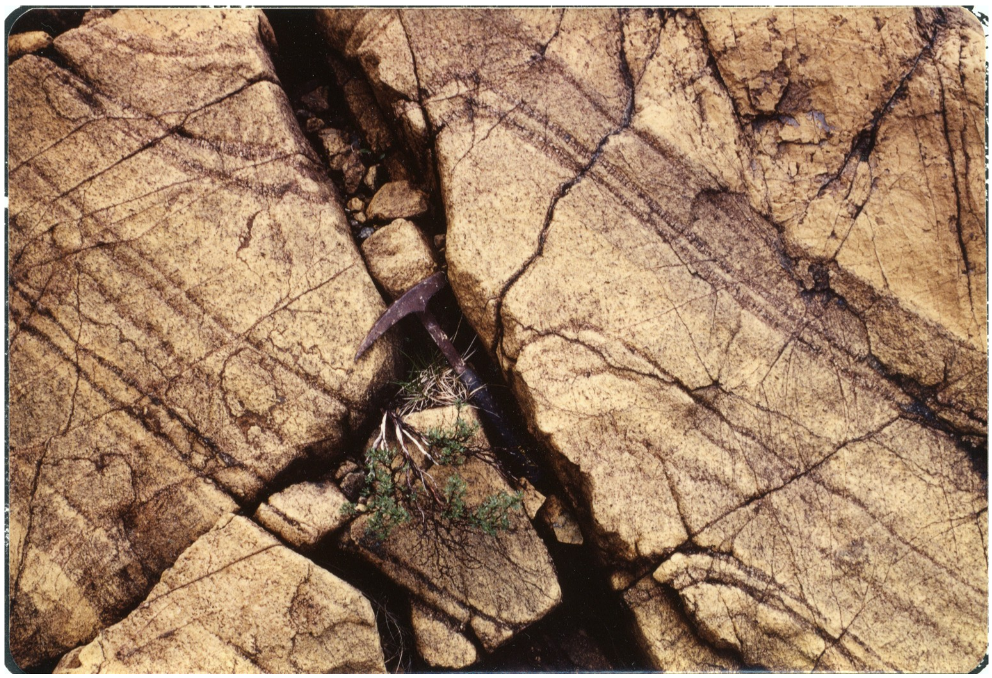

Figure IV-10C: Ductile shear zones. Small kink fold which disrupts both the enstatite layers and the S_1 foliation which lies parallel to them. Note thick dunite layer at the very top of the photo.

disruption of structure has been identified across any of these zones. On the basis of the nature and scarcity of these zones, no support for major tectonic shortening of the harzburgite section is in evidence on Table Mountain.

Brittle Jointing and Faults

Pervasive non-penetrative conjugate joint sets are in evidence throughout the massif. They are best exposed along the northern and southern faces (Frontispiece and Figure IV-1). The jointing does not significantly offset crosscutting features (i.e. the foliation and intrusives) and no vein filling or grain size gradation within the country rock is present.

Due to the brittle appearance of this system and its conjugate orientations across the relatively tabular massif, it is assumed that these features are related to late-stage deformation associated with the final emplacement of the nappe.

A variety of brittle faults and shear zones have also been recognized. These are marked by zones of intensely developed anastomosing slickensided surfaces. Beautiful, shiny flakes of fresh serpentine cover the blocks within the zones. Very rarely, the zones are rodingitized. The apparent offsets along these faults are quite variable. The bulk of the faults within the massif show minor offset (less than 15 meters). However, along the northwest margin of the massif, a fault truncates the contact between the cumulates and the residual tectonites, apparently downdropping the northern portion 120 meters (Plate A).

The faults bounding the massif have already been briefly discussed but will be reexamined here. The basal thrust is traceable from Winter House Brook (Figure IV-11) along the eastern margin of the mountain to its intersection with the eastern end of Upper Trout River Pond. Here the fault dips approximately 60 degrees to the west. A large tear fault separates Table Mountain from North Arm Mountain. Over 1000 meters of topographic relief occurs across this fault (This includes the depth of Trout River Pond). To the west, a thrust fault separates the Coastal Complex from Table Mountain. It is buried in scree shed off the mountain. Outcrop patterns suggest that it is relatively shallow, dipping towards the east. The nature of the northern fault separating the Coastal Complex from Table Mountain is poorly understood. Its trace is lost under the alluvium of the Gulch along Route 44.

An interpretive map of these late-stage faults has been compiled using Girardeau's data from the cumulate portion of the massif and geological mapping and air photo interpretation undertaken by the author (Figure IV-12). The regular pattern of faults seems to parallel the large tear fault along Trout River Ponds. This would argue for an emplacement-related origin for the brittle faulting.

Large Scale Folding of the Table Mountain Massif

Previous observations by Williams (1973), Karson and Dewey (1978) and Casey and Kidd (1981) indicate that the Table Mountain, North Arm Mountain and Lewis Hills Massifs display gentle to tight synformal

Figure IV-11. The basal fault contact of the Table Mountain Massif against the Humber Arm Sequence near its northeast corner in Winter House Brook. The foliated gray rocks to the right of the fault are highly sheared totally serpentinized harzburgites. The white resistant material along the fault is rodingitezed fault gouge in which xonotlite has been identified.

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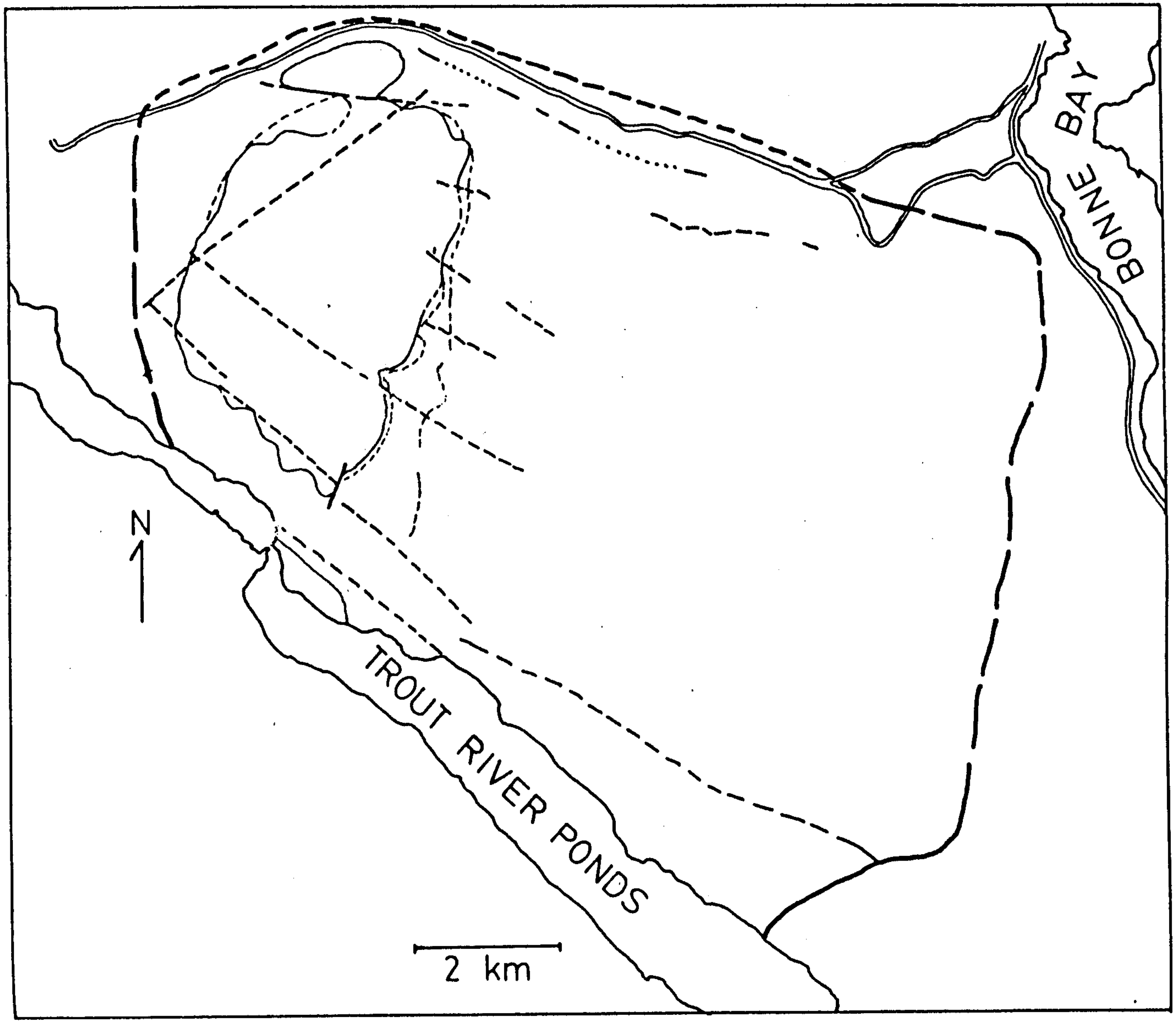

N
TROUT RIVER PONDS
BONNE BAY
2 km

structure with hinge lines lying roughly NNE with low plunges. In order to construct valid models of oceanic ridge systems, it is imperative to ascertain the structural associations and geometries of ophiolitic slabs prior to obduction. Any reconstruction of Table Mountain must rely upon the following assumptions: 1) The contact between the cumulates and the residual tectonites was originally a flat planar surface - ignoring the small scale interdigitations. 2) The S_1 foliation may also be considered to be a flat planar surface over a 1 to 5 km interval. Systematic fanning of S_1 may occur at depth. 3) The dynamothermal aureole which has been shown to have been generated at the initiation of obduction (Jamieson, 1979) must have formed with an initial dip of 0 to 30° E.

Mapping by the author (Plate A), O'Connell (1979) and Girardeau (1979) indicate that the large scale surface between the cumulates and the tectonites is a very gentle synformal structure with an axis plunging WSW10°. This contact is nearly flat-lying in many places although the outcrop pattern has been disrupted by late-stage normal faulting. On the other hand, the present orientation of the dynamothermal aureole preserved along the eastern face of the massif is 60°W. This indicates that a minimum of a 30° angular rotation has occurred between the base of the ophiolite and the cumulate section.

Further information concerning the nature of this rotation of the base of the section relative to the chosen paleo-horizontal surface may be gleaned by examining the fluctuations in the orientation of the S_1 foliation. Within the harzburgites, the S_1 foliation shows remarkably constant orientation along-strike. Ignoring minor deflections adjacent to obduction related faults, the foliation shows only two significant variations in attitude. The first is a 20 to 40° steepening of the dip along an approximately 1 km thick zone immediately east of the belt of transitional dunites exposed on the top of the mountain. This zone is not apparent on Plate A but may be clearly seen in Girardeau's (1979) data for the entire massif. The second variation is a gradual fanning of the foliation - a 15 to 30° eastward swing in strike and up to a 10° decrease in dip. This occurs from the western wall of Winter House Brook eastwardly to the margin of the massif.

The consistently linear trends of the strike of S_1 across the top of the mountain suggest that if significant folding of the ophiolite occurred during or after obduction, the hinge line should be approximately parallel to the strike. The previously mentioned variations in the orientation of S_1 suggest that the deformation resulting in the minimum of a 30° rotation or flexure of the harzburgite section did not affect the tectonites homogeneously. Further evidence for this includes the presence of undeformed dunite and orthopyroxenite dikes cross cutting the harzburgite in a variety of orientations as well as no evidence of large scale folding of S_1 nor overprinting of the small scale folds preserved along intrusive bodies.

The S_1 foliation within the lower cumulates is much more irregular than that within the harzburgites. Most of the erratic orientations may be related to the numerous late stage normal faults truncating the western portion of the massif. Girardeau's (1979) map indicates that within the main exposure of the cumulates (the northeast two-thirds of the unit) the foliations systematically change orientations from an average of N25E 50W in the north to N50E 75W in the south. The foliation measurements in the western exposures are irregular and outcrops are scarce. The available data does suggest that dips are near vertical. Measurements of compositional layering indicate that it swings around the southeast corner of the cumulates as well - along the eastern exposure measurements averaged N50E 65W while the southern outcrops yield values N70E 50N and EW70N (O'Connell, 1979). Available data on the S_1 foliation in the adjacent residual tectonites does not show this deflection. Therefore, the apparent tight synformal structure of the cumulate suite must be related to crustal processes active along the ocean ridge axis and not the result of later regional or obduction related deformation.

Any attempt to restore a more plausible angular separation between the cumulate/tectonite contact and the dynamothermal aureole will accentuate the progressive fanning of the S_1 foliation down-section. Structural petrology data indicates that the basal harzburgites (approximately 1 km thick) have experienced considerably greater strain than the remainder of the nappe. In addition, some overprinting of S_1 has been described (Mercier, 1976; Girardeau, 1979; Girardeau and Nicolas, 1981). It is conceivable that the deformation responsible for the present orientation of the aureole is restricted largely to this zone. Further study will be required to completely resolve this problem.

Summary

The Table Mountain Massif shows an apparent gentle synformal structure. The nearly flat-lying contact between the cumulate suite and the residual tectonites is slightly synformal with the axis plunging WSW 10°. If one is willing to assume that the basal thrust contact of a large ophiolitic nappe (e.g. the Bay of Islands or Semail Ophiolites) is essentially flat-lying upon obduction, then the northern massifs of the Bay of Islands are tight to open synformal structures. For Table Mountain, the orientation of the axis is approximately NE/SW. A similarly oriented synformal structure has been reported for the North Arm Massif by Casey and Kidd (1981).

Three other mesocopic features of the massif are significant:

1. A zone of penetrative deformation extending upward from the residual harzburgites approximately 500 meters into the basal cumulates. The deformation structures are consistently oriented with those in the underlying harzburgites and the apparent sense of shear affecting the basal cumulates is identical to that affecting the upper harzburgites.
2. Highly deformed dunite lenses that range from 10 to 300 meters in thickness and up to 5 kilometers in lateral extent (Plate A and Quick, in press). These lie at the base of the cumulates and have a gradational contact with the residual harzburgites.
3. A fanning in strike of the S_1 foliation and associated spinel and enstatite lineations progressively down-section through the harzburgites. Two hiatuses within the gradual change are recognized and correlate with the textural and sense of shear

inversions of Girardeau (1979) and Girardeau and Nicolas (1981). These may correlate with large-scale ductile shear zones initiated during earliest stages of obduction.

CHAPTER V

STRUCTURAL PETROLOGY

Kinematic Analysis

The theory and approaches to kinematic analysis of deformed rocks have been discussed in a number of texts (e.g. Turner and Weiss, 1963; Ramsay, 1967; Nicolas and Poirier, 1976). As Turner and Weiss stated:

> The observed final state of a deformed body is compared with some assumed initial state, and a path of kinematic development is proposed. But even from the same observations and assumptions regarding parent states, more than one kinematic reconstruction is possible.

The interpretation of rock fabric evolution heavily involves the application of the techniques and theory of physical metallurgy. These may be broken down into four elements: 1) Determination of rock textures and preferred mineral orientations; 2) Experimental work to define the physical properties of the rock-forming minerals; 3) Determination of the dominant flow mechanisms in the minerals; and finally 4) Determination of the relationship between the mineral aggregate fabrics and the geometrical nature of the flow.

A fundamental problem in the analysis of residual peridotite tectonites is the determination of the nature of an inital state. Mercier and Nicolas (1975) attempted to assign a chronological sequence to the textures which have been identified in tectonized peridotites. Their proposed cycle is reproduced in Figure V-1. Some evidence for this cycle is preserved in the suite of samples collected from Table

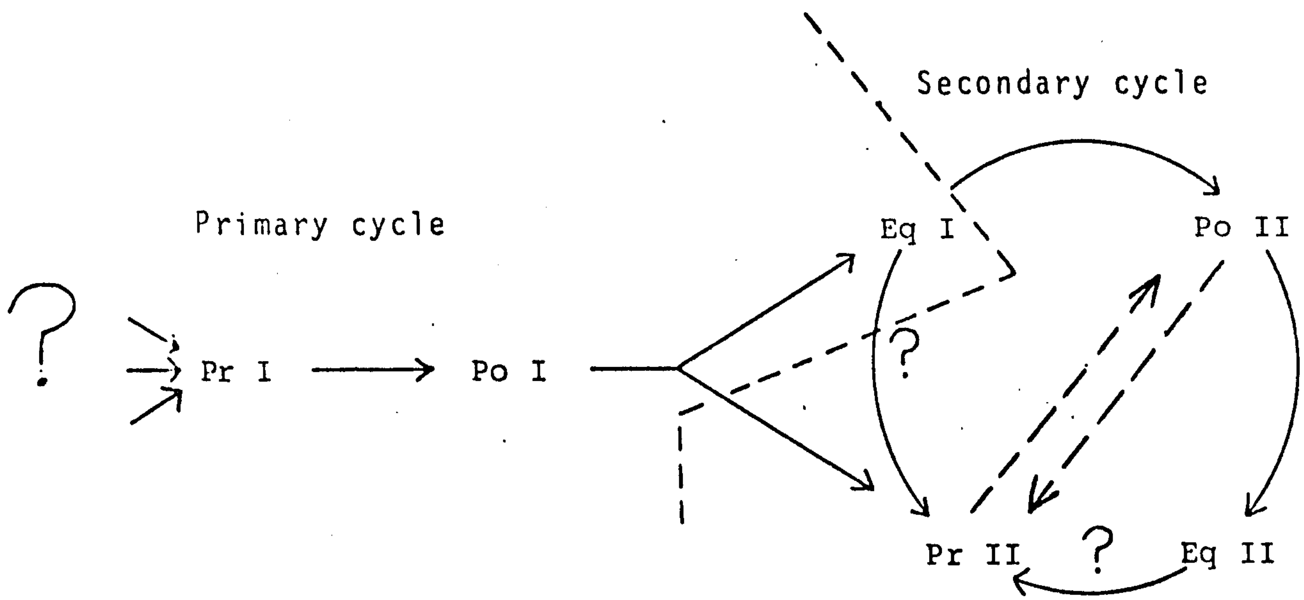


Figure V-1 Schematic diagram of possible textural evolution within the upper mantle. Pr I represents an initial protogranular texture, Po I is the resulting porphyroclastic texture, Eq I is the equilibrium equigranular texture (also see R.J. Twiss). II prefixes indicate second generation textures. (Adapted from Mercier and Nicolas 1975)

Mountain (see Chapter III for a further discussion). A pure equigranular texture has not been observed within the samples gathered from the tectonized assemblages of the Bay of Islands Massifs. Instead, a tabular equigranular texture is typical of nearly all the dunite bodies. This is most likely a function of temperature and strain rate within the system away from the ridge axis. Should it have merely been the result of the system being within one textural phase, some remnant areas of equant equigranular texture should have been preserved in places, possibly at different structural levels within the tectonites. Observations from other ophiolites (e.g. Trinity, Burro Mountain, Cyprus and Semail) indicate that olivine is often tabular with some recrystallization of the more elongated grains. This could support some cycling of textures between equigranular and porphyroclastic.

No primary strain markers are preserved in the harzburgites. It is likely that the enstatite crystals have experienced competing processes while undergoing plastic strain. Simple shear elongation would increase the grain aspect ratio initially. A variety of mechanisms which would locally reduce the apparent grain elongation have recently been summarized by Means (1981). These include vorticity effects, boudinage, shear truncation, growth of porphyroblasts, and a variety of recrystallization mechanisms. This casts doubt on the validity of Girardeau and Nicolas' discussion of enstatite and olivine aspect ratios as a supporting observation indicating the amount of strain sustained by the harzburgites.

The crosscutting intrusive bodies or conduits would at first appear to be obvious useful strain markers. Penetrative and non-penetrative deformation of dikes often gives indications of the relative sense of shear affecting the rock. Field evidence from the Bay of Islands Complex suggests that the "intrusives" preserved within the residual tectonites have been emplaced over a substantial time interval with respect to the development of the foliation (this could possibly be as much as 10 ma.). It is also probable that the earliest intrusives are now completely transposed and unrecognizable. Any valid structural analysis must therefore be limited to a discussion of processes active since the formation of the oldest recognized texture (protogranular).

The approach to kinematic analysis of a residual tectonite adopted here is that advanced by Nicolas and Poirier (1976). It involves relating those penetrative structural elements observed in the field (foliation and lineations) and in thin section (foliations, lineations, and preferred crystallographic orientations) to the three orthogonal kinematic axes: a) the principal direction of flow (assuming simple shear) this is approximated by the point maxima of the slip directions $[100]_{ol}$ and $[001]_{en}$; b) the perpendicular to a in the flow plane; and c) the normal to the flow plane (approximated by $(010)_{ol}$ for high temperature or $(001)_{ol}$ for low temperature and by $[100]_{en}$) (Nicolas and Poirier, 1976). With adequate information, the direction and relative rate of flow may be determined. Figure V-2 depicts the relationship between the kinematic axes, fabric symmetry

Figure V-2. Diagram relating the principal strain axes, the kinematic axes and the fabric symmetry axes to the crystallographic axes (preferred orientation) of forsterite resulting from plastic flow.

Principal Strain Axes:

$\varepsilon_1 > \varepsilon_2 > \varepsilon_3$

Kinematic Axes:

a principal direction of flow

b the perpendicular to _a_ in the flow plane

c the perpendicular to the flow plane

Fabric Symmetry Axes:

A mineral lineation

B the perpendicular to the lineation within the foliation plane

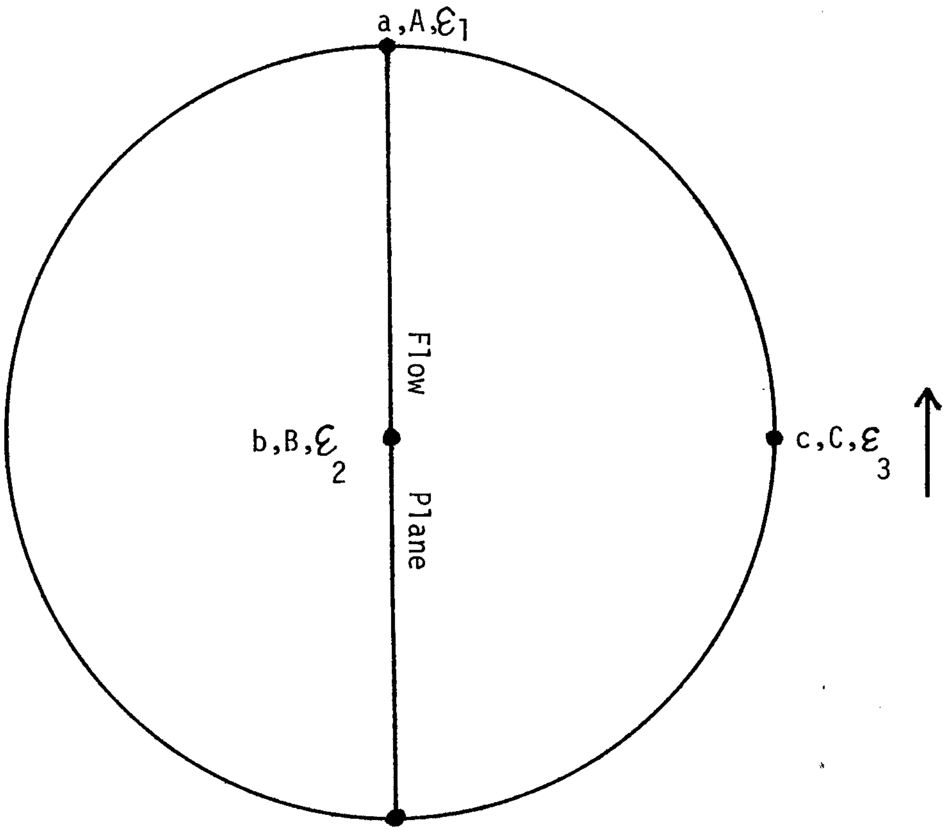
C the perpendicular to the foliation

Crystallographic Axes (preferred orientations for forsterite):

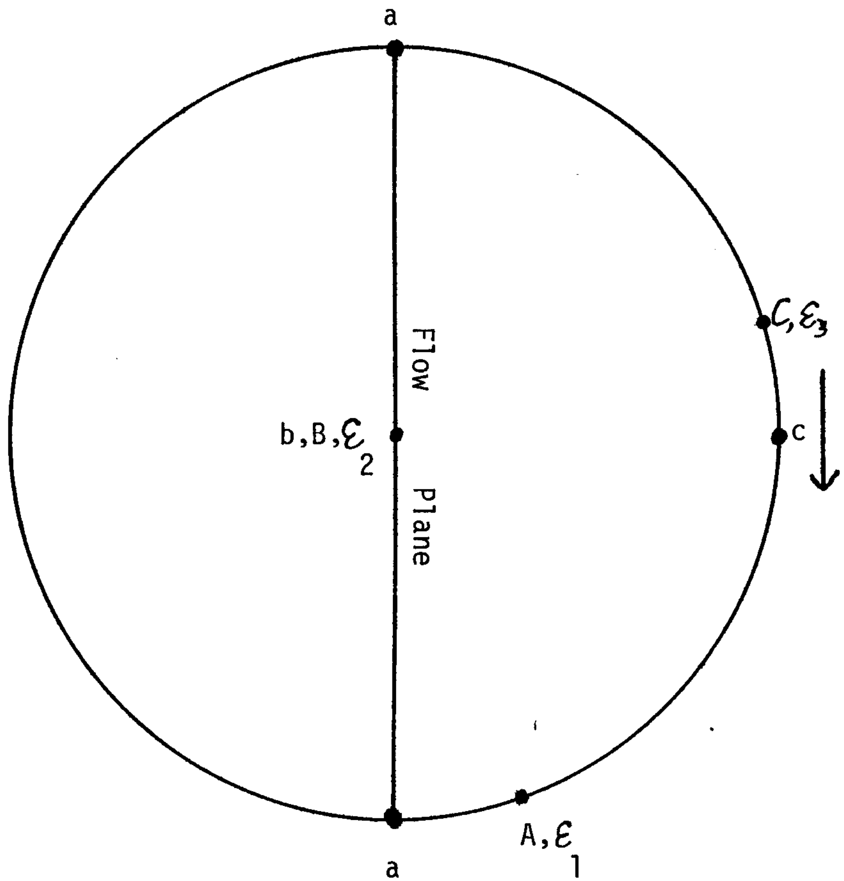
X (b)

Y (c)

Z (a)



Pure Shear



Simple Shear

axes and the maxima of crystallographic axes of olivine which are generated by various dominating slip systems.

Highly deformed rocks generally display a crystallographic preferred orientation of some or all of the constituent minerals. This has been clearly demonstrated for the tectonized peridotites and deformed lower cumulate suites of ophiolites (e.g. Ross, 1977; George, 1978). Hobbs, Means and Williams (1976) discussed two main mechanisms by which such preferred orientations could develop: 1) under conditions of low temperature and/or high strain rate where recrystallization does not occur, by rotation of inequant grains or by slip within grains accompanied by rotation; 2) by widespread recrystallization within a stress field.

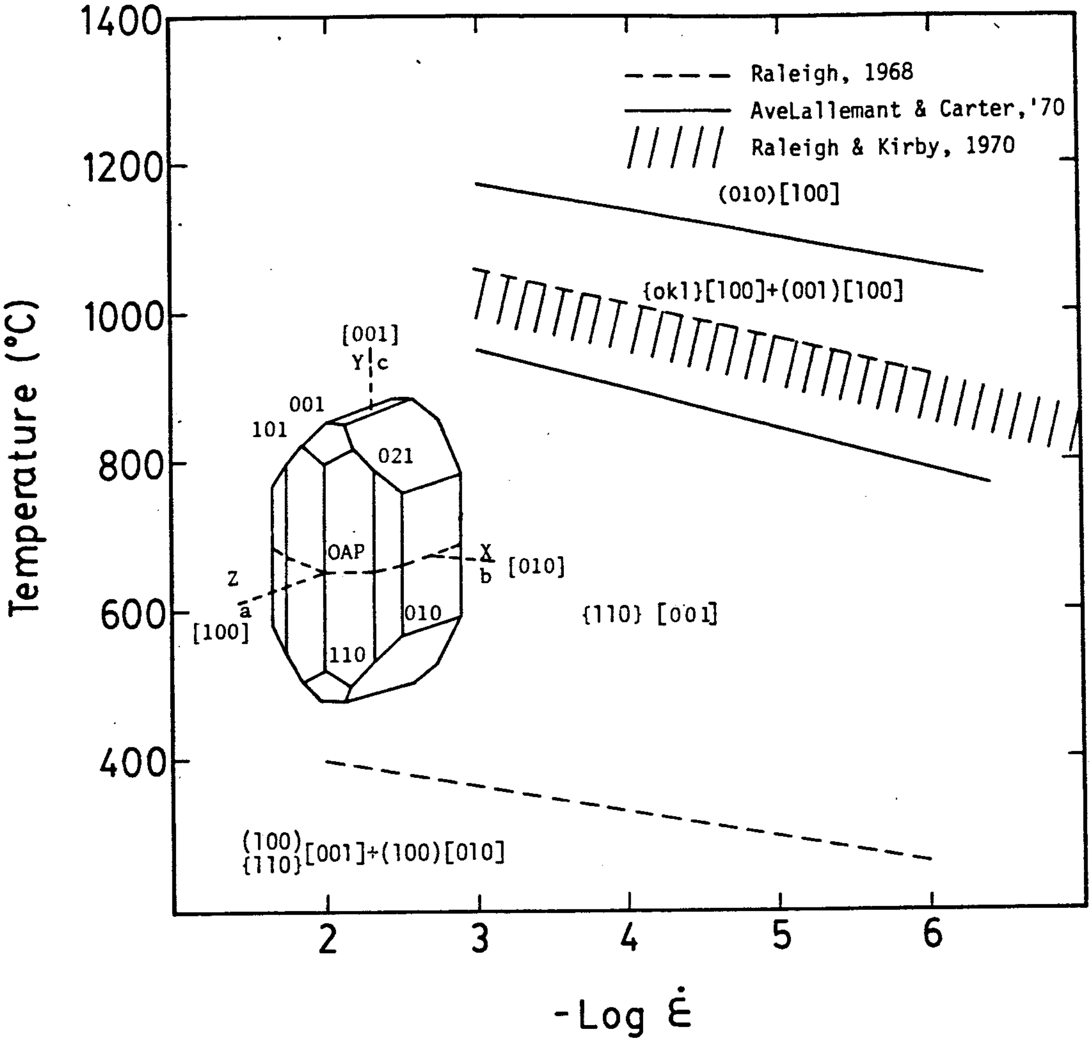
The experimental deformation (uniaxial and triaxial pure shear) of initially random olivine aggregates has produced the following textures:

[010] migrates toward the σ_1 direction (compressive) where $\sigma_2 = \sigma_3$; no maxima of [100] or [001] develop.

Intracrystalline slip has been shown to be important in the production of these textures by the study of inclusions which serve as strain markers.

Syntectonic recrystallization also produces grains with [010] oriented parallel to σ_1 and [100] parallel to σ_3 (e.g. Raleigh, 1968; Carter and Avé Lallemant, 1970).

Nicolas and Poirier (1976) have summarized many of the flow studies conducted on European ophiolites. For cold working conditions with rotational shear flow (non-coaxial progressive simple shear), enstatite grains show no significant preferred orientation while olivine displays [100] density maximum close to the lineation trend but symmetrically inclined to it by approximately 20 degrees in the plane defined by the lineation and the normal to the foliation. A large amount of flow occurs with slip on the systems (010) [100] and {okl} [100]. Under hot working conditions with dominant rotational shear flow (more typical of ophiolite tectonites), $[100]_{ol}$ (the dominant slip direction at high temperature) shows a good point maximum inclined less than 20 degrees to the lineation while $[010]_{ol}$ concentrates in a maximum at about 60 degrees to the foliation. These textures indicate that the dominant slip plane active in olivine is (010). The $(010)_{en}$ slip direction would then coincide with $[100]_{ol}$ while $[100]_{en}$ would coincide with $[010]_{ol}$. Furthermore, Nicolas and Poirier conclude that, as a result of metallurgical and experimental studies of mineral aggregates, plastic flow (rotation and slip) dominates the formation of crystallographic preferred orientations under cold working conditions. Figure V-3 summarizes the experimentally verified glide systems of olivine. Under hot working conditions where recrystallization is prevalent, Nicolas and Poirier concede that constraints on the system are very poorly understood and, consequently, interpretation of preferred orientations is speculative. They propose that the study of large porphyroclasts which were likely shaped by the initial



Experimentally verified glide systems of olivine as a function of temperature and strain rate.

(Nicolas and Poirier 1976)

plastic flow and subsequently isolated by recrystallization should only reflect the history of the active flow prior to recrystallization.

One promising approach to this problem has been the deformation of organic crystals within 80 to 90 percent of their melting temperatures in an apparatus allowing continuous microscopic examination of the evolving textures (Means and Xia, 1981). While no definitive results have as yet been obtained regarding the modification of crystal fabrics by annealing recrystallization, this technique enables a researcher to specifically control the parameters of deformation and hence will prove invaluable in the study of fabric evolution.

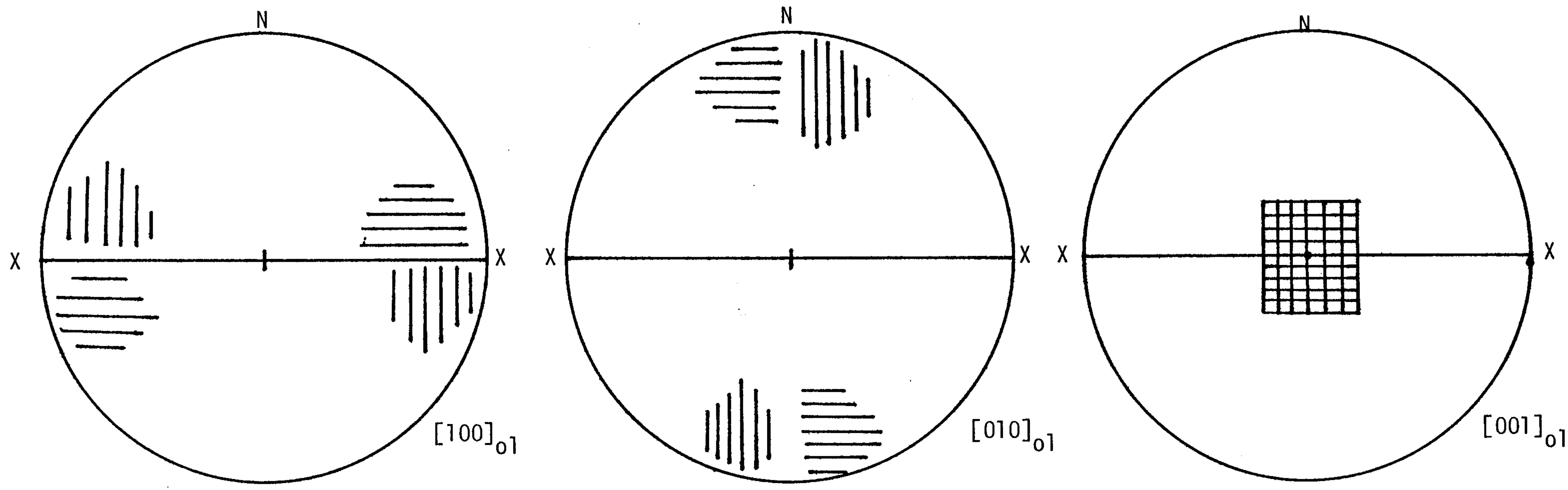
At the moment, however, relict structures are the only keys to the effects of recrystallization on initially strain-induced fabrics. George (1978) noted that peridotites deformed as a result of syntectonic recrystallization (Ave Lallemant and Carter, 1970) or by plastic flow (Nicolas et al, 1973) typically show $[010]_{01}$ maxima nearly normal to the S_1 foliation and $[100]_{01}$ maxima approximately parallel to the enstatite and spinel lineations. However, the strong olivine fabrics and lack of strong foliation of several samples collected from the ultramafic metacumulates of the Troodos Ophiolite could not have been produced by any of the known flow mechanisms of olivine in a single deformation. George suggests that annealing recrystallization may have modified the textures and fabric in this case.

Sense of Shear Determinations

Nicolas and Poirier (1976) claim that the oblique relationship between the preferred orientation of olivine and the structurally penetrative foliation and lineations record the sense of shear experienced in the peridotite. To determine this, the nature of the flow must first be determined (i.e. if it is irrotational, then the spinel and/or enstatite lineation will be coaxial with the principal flow direction). If, on the other hand, rotational shear flow occurred, the principal flow direction and the flow plane will lie at a small angle to the foliation when measured along the trend of the lineation. The oblique relationship of the $[100]_{01}$ maxima to the spinel lineation within the S_1 foliation is therefore suggested to indicate rotational flow. Figure V-4 depicts the geometric relationship between the olivine maxima and the structural axes.

Micro-textural criteria may also be invoked. These primarily involve the observation of glide within enstatite crystals. Nicolas and Poirier (1976) noted that elongated enstatite crystals (aspect ratios of approximately 6:1) may show simple shear displacements in the opposite sense to the deformation experienced by the bulk of the rock. The long axis of these enstatite crystals is oriented in a locking orientation to the shear affecting the system. As the majority of orthopyroxene crystals show the same shear sense as the large-scale system, non-coaxial progressive simple shear may be inferred.

Etchecopar (1980) geometrically modeled progressive deformation of a polycrystalline aggregate assuming that dislocation glide was the dominant flow mechanism. His results indicate that two maxima may develop symmetrically disposed to the elongation direction and that the stronger of the two indicates the sense of shear. Some olivine



Vertical lines -- the expected point maxima for dextral shear sense.

Horizontal lines -- the expected point maxima for sinistral shear sense.

In natural rocks olivine porphyroclasts give more consistent groupings than neoblasts, although both show the same relative configurations. The projection is plotted on an equal area stereonet (lower hemisphere). The foliation is represented by the vertical EW plane and the 'X' depicts the trace of the lineation. (Theory and observations of natural systems by Nicolas and Poirier 1976 and by Lister 1979).

Figure V-4

crystals clearly experience deflection of their [100] axes in the opposite sense to that experienced by the rock system. This phenomenon is likely more indicative of rotational shear flow.

<u>Petrofabric Analyses of the Bay of Islands Complex</u>

Petrofabric analyses have been conducted on all of the massifs within the Bay of Islands Complex (Mercier, 1976; Girardeau, 1979; Christensen and Salisbury, 1979; Girardeau and Nicolas, 1981). The division of the ultramafic suite has largely been made on the basis of the amount and nature of deformation which affected the various units. Mercier (1976 a) divided the Bay of Islands suite into the following groups (see Chapter III for a more complete discussion):

1. Enstatite-free ultramafics (cumulate): these range from dunite to diopside-rich feldspar wehrlite. The flow structures are identical to those in the gabbros. No evidence of high temperature solid-state deformation has been described.

2. Cumulate dunites: the chrysotile olivines have abundant microinclusions. Green and Radcliffe (1975) argue that such an observation indicates an absence of solid state deformation.

3. Porphyroblastic dunites: these display a bimodal grian size distribution in which the large porphyroblasts are nearly unstrained. Strong olivine fabrics have also been documented.

4. Protogranular harzburgites:
   a. Upper zone: enstatite grains show strong [001] elongation due to deformation of the crystals (the grains are optically unstrained and recrystallization is extremely limited).
   b. Lower zone: characterized by equant enstatites with curvilinear grian boundaries.

5. Blastolaminar lherzolites: the olivine paleoblasts have a strong (100) maximum subparallel to the enstatite lineation. Slip systems active in low temperature, high strain fields are dominant.

Further work on the deformed cumulate and harzburgite fabrics was undertaken by Girardeau (1979), Christensen and Salisbury (1979), and Girardeau and Nicolas (1981). The latter researchers give a more detailed discussion of the structures and fabrics observed on Table Mountain and Blow Me Down Mountain which better agrees with the results of this study. They distinguish the following groups:

1. Upper and lower gabbros: These display adcumulate and orthocumulate textures. Local, sparse shear zones are observed in two sets of preferred orientations, one parallel to layering with a dextral sense of shear, while the other is more oblique to layering (and displays the same sense of shear?). Girardeau and Nicolas suggest that these occurred after the consolidation of the gabbros.

2. Basal gabbros: This unit has been plastically deformed at high temperature with the [100] (010) slip system controlling olivine deformation. Annealing recrystallization of the olivine paleoblasts has occurred.

3. Upper peridotites: These include fine-grained porphyroclastic harzburgites and equigranular or occasionally tabular dunites. The spinel grains are strongly elongated. Girardeau and Nicolas claim that a high temperature rotational regime was active with the [100] (010) slip system dominating the deformational mechanisms. Significant strains are inferred.

4. Lower peridotites: Again, fine-grained porphyroclastic texture is common; however, orthopyroxene grains are not elongated, spinel only slightly so. A strong preferred orientation with the olivine [100] (010) slip system domination the rotational regime is inferred.

5. Basal peridotites: Porphyroclastic textures are pervasive. Again, the [100] (010) slip system is active. Very well developed olivine fabrics and elongation of mineral grains suggest extreme strains.

Girardeau's determination of the olivine fabrics of samples collected from the tectonized suite of Table Mountain all show $[100]_{01}$ maxima symmetrically disposed about the S_1 foliation. The olivine fabrics of the deformed cumulates are weak but are clearly consistent with the strong fabrics of the foliated dunites and upper harzburgites. In his structural petrology study of the Troodos Ophiolite, George (1978) observed that the fabrics of the deformed metacumulates are consistently stronger than those of the undeformed suite. He argued that this is the result of tectonic modification of an original cumulate fabric. While no petrofabric data is available from the uppermost cumulates exposed on Table Mountain, mesoscopic structural data clearly indicates that none of the penetrative deformation-related features observed in the basal cumulates and tectonites are present. The foliated dunites display stronger $[100]_{01}$ maxima than the basal cumulates. There is also a slight strengthening of the olivine fabrics progressively down-section in the harzburgites (this thesis and Girardean and Nicolas, 1981). The optical determinations of these fabrics undertaken by Christensen and Salisbury (1979) and Girardeau and Nicolas (1981) are shown in Figure V-5. Using the relationship of $[100]_{01}$ maxima to the S_1 foliation, an interpretation of the sense of shear has been made and is indicated for each sample (Etchecopar, 1974). In the case of Christensen and Salisbury's data, the orientation of S_1 was first determined from Plate A and then superimposed on their diagram.

In order to obtain more complete information on the possible variation of olivine fabrics progressively down-section in the massif, the author analyzed five additional samples from the harzburgites. Figure V-6, a sketch map of the massif, depicts the location of all samples discussed in this chapter.

Figure V-5A. Optically determined olivine fabrics for samples collected from Table Mountain by Christensen and Salisbury. (after Christensen and Salisbury, 1979). (Projections in geographic space, lower hemisphere)

Sample 157: "plagioclase periodotite" - most likely a troctolite. The sample is from the deformed cumulates just above the dunites on the northern face of the mountain.

Sample 161: "ultramafic tectonite" - sample location is in the uppermost harzburgites along the northern slope.

Sample 164: "ultramafic tectonite" collected midway along northern face.

Sample 162: "ultramafic tectonite" collected from N.E. Winter House Brook.

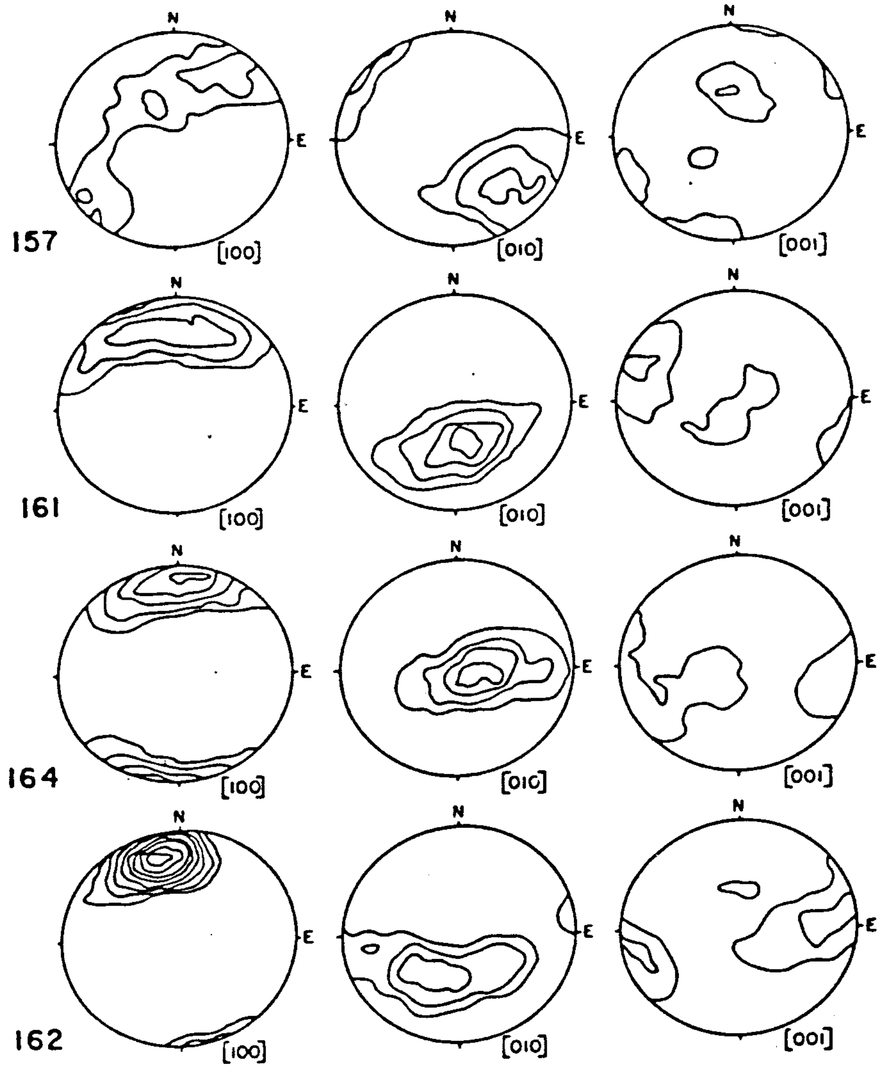

N
E
157
[100]
[010]
[001]
161
[100]
[010]
[001]
164
[100]
[010]
[001]
162
[100]
[010]
[001]

Figure V-5B. Olivine fabric data published by Girardeau and Nicolas (1981) for Table Mountain. Projections are normalized to structure space. Solid line is the foliation. Solid dot is the lineation.

Sample A: Fine-grained porphyroclastic lherzolite from the basal zone (96 measurements; contours: 1, 4, 6, 10%). Sinistral shear sense.

Sample B: Fine-grained porphyroclastic harzburgite from the lower zone (50 measurements; contour: 1, 4, 8, 10%). Dextral shear sense.

Sample C: Equant equigranular dunite from the upper zone (101 measurements; contours: 1, 4, 6, 8%). Dextral shear sense.

Sample D: Olivine gabbro with ribbon texture from the basal cumulate zone (102 measurements; controus: 1, 2, 4, 5, 6%). Indeterminate shear sense.

Sample E: Troctolite with ribbon texture from the basal cumulate zone (97 measurements; contours: 1, 2, 3, 4%). Indeterminate shear sense.

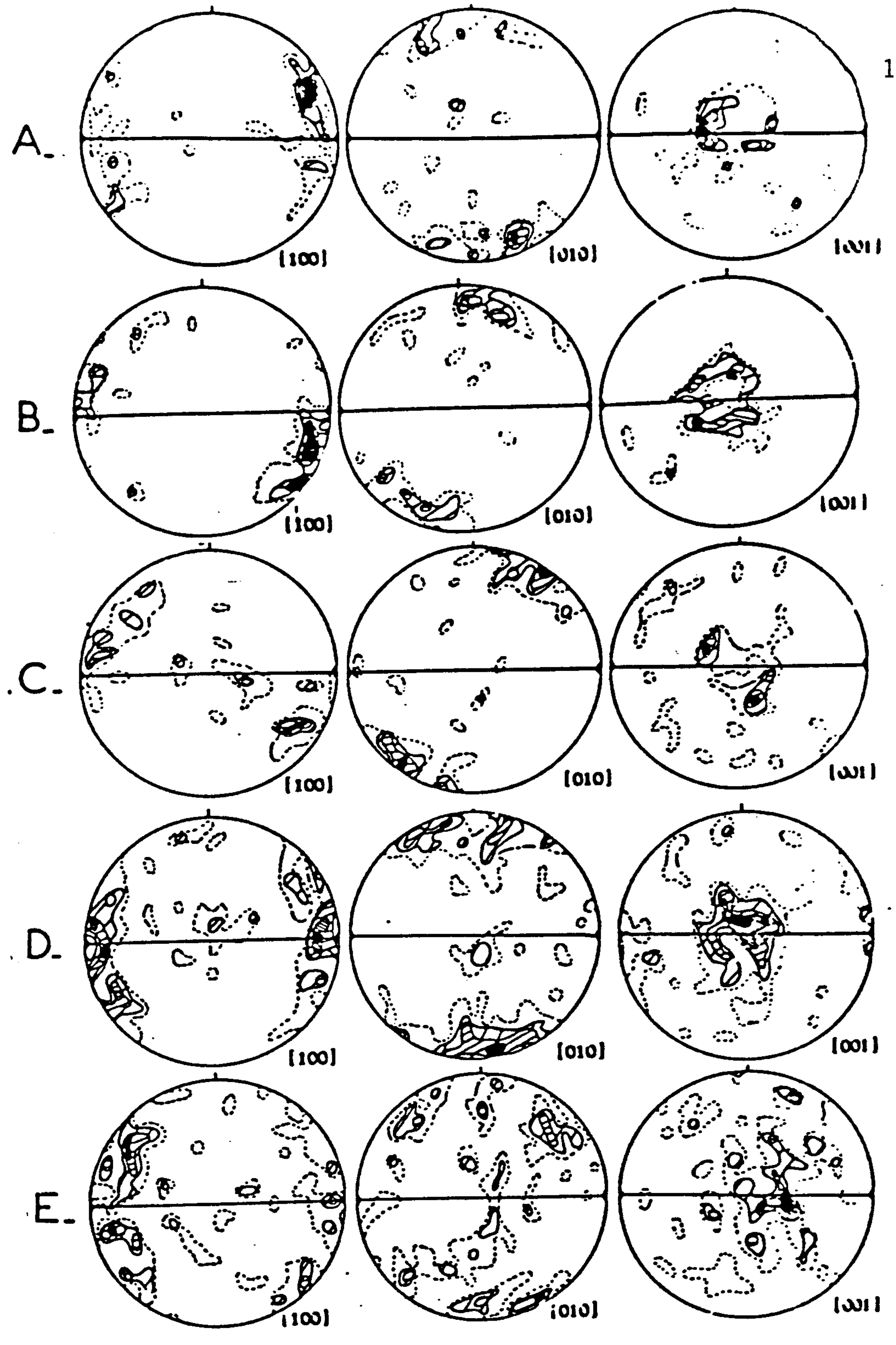
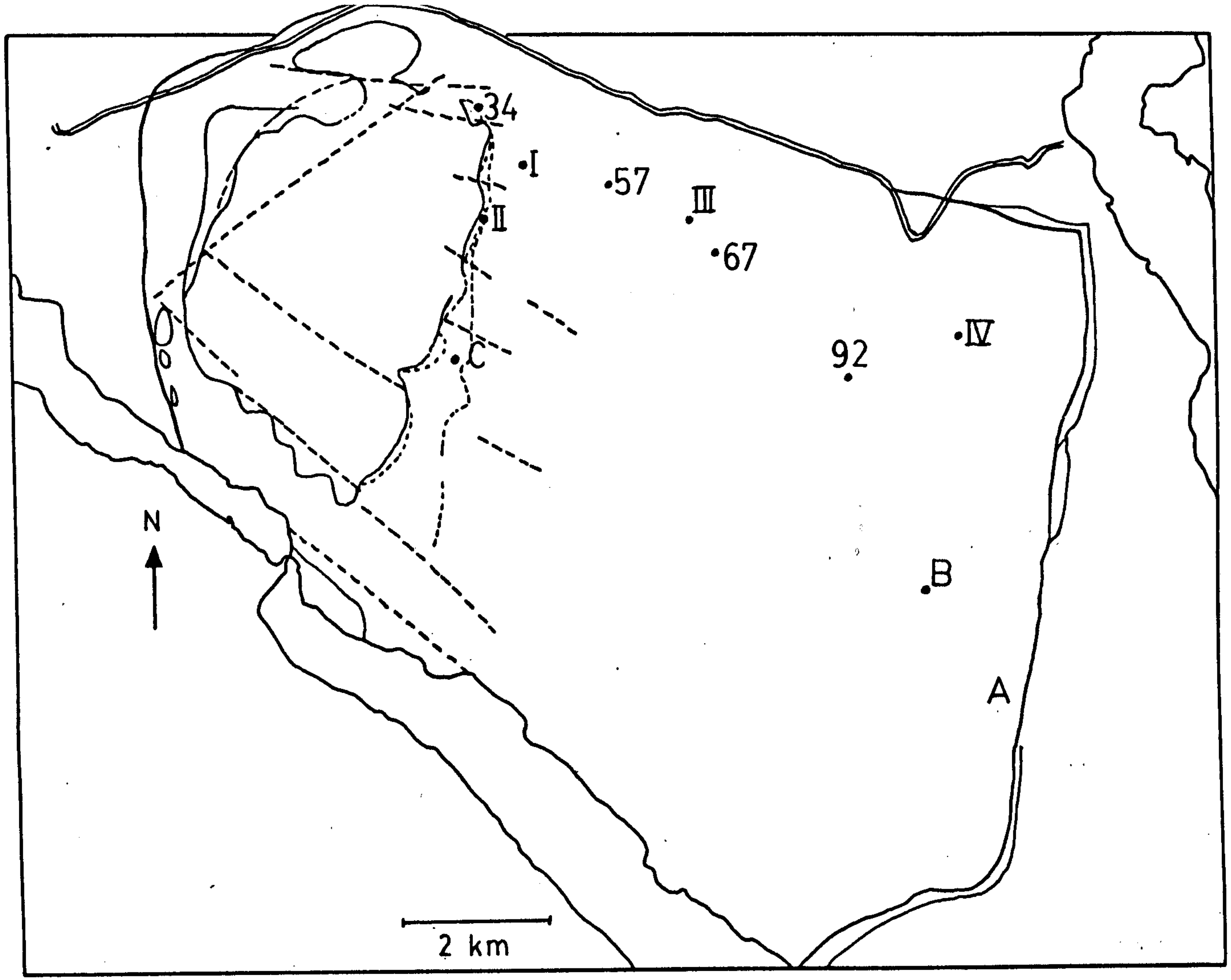

A.
[100]
[010]
[001]
B.
[100]
[010]
[001]
C.
[100]
[010]
[001]
D.
[100]
[010]
[001]
E.
[100]
[010]
[001]

Figure V-6. Simplified map of Table Mountain (after Girardeau, 1979) locating the samples analyzed for petrofabric data. For clarity, Christensen and Salisbury's (1979) samples have been renumbered. I represents their sample 161. II represents their sample 157. III represents their sample 164. IV represents their sample 162. Girardeau and Nicolas (1981) primarily used data presented in Girardeau (1979) although several new samples were included, but no location other than rock type and zone was given for these. Samples published in Girardeau (1979) are located by capital letters corresponding to those in Figure V-1B. The five samples analyzed in this thesis are also shown.


34
I
57
II
III
67
C
92
IV
N
B
A
2 km

Olivine Fabric Data from Table Mountain

Five samples collected by the author along the northern face of Table Mountain have been analyzed for olivine preferred crystallographic orientations. In the field, careful attention was given to sampling representative harzburgite displaying structural continuity with the entire outcrop. Individual outcrops were selected to avoid emplacement-related faulting and deformation, or slump along the cliff faces.

Oriented thin sections were cut from the samples in two orientations: one parallel to the foliation and one perpendicular to it in the direction of the spinel or aggregate enstatite lineation. Orientation determinations were undertaken using a Leitz five-axis universal stage. Data collected in thin section space was normalized to structural space using a Wulff stereonet. For density contouring, the points were plotted on an equal area stereonet. The results are given in Figure V-7.

The strength of the fabrics shows a gradual increase progressively down-section from the transitional harzburgite (as manifested by $[100]_{ol}$ maxima). This trend is more clearly seen when the determinations presented here are examined in conjunction with the results of Christensen and Salisbury (1979) and Girardeau and Nicolas (1981) given in Figure V-1A and V-1B. The deformed cumulates have the weakest olivine fabrics. When projections are normalized into structural space with the S_1 foliation vertical and L_1 horizontal, [100] axes show great scatter about L_1 although slight concentrations of points suggest that the rock experienced a sinistral sense of shear. This is

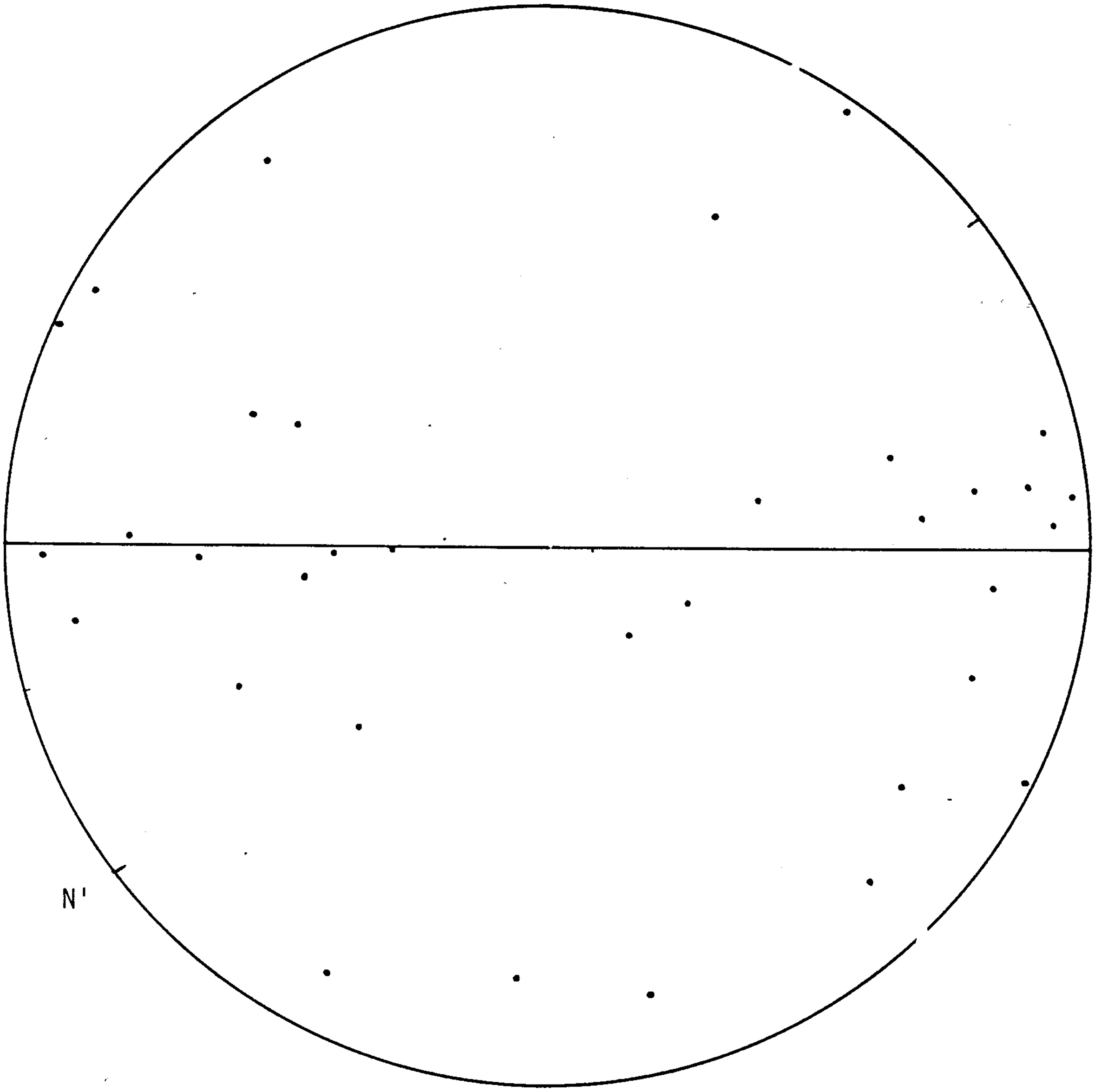
Figure V-7. Olivine fabric data for samples collected from the harzburgite suite exposed along the northern face of Table Mountain. The projections are lower hemisphere (equal area net) and have been normalized to structure space. The solid line represents the S_1 foliation, L_1 is horizontal and within S_1.

B-34 This sample was collected from the upper harzburgites immediately below the transitional harzburgites. It has porphyroclastic texture and sparse interstitial clinopyroxene. The foliation has an orientation of N50E 75NW. A sinistral shear sense may be inferred. (38 measurements)

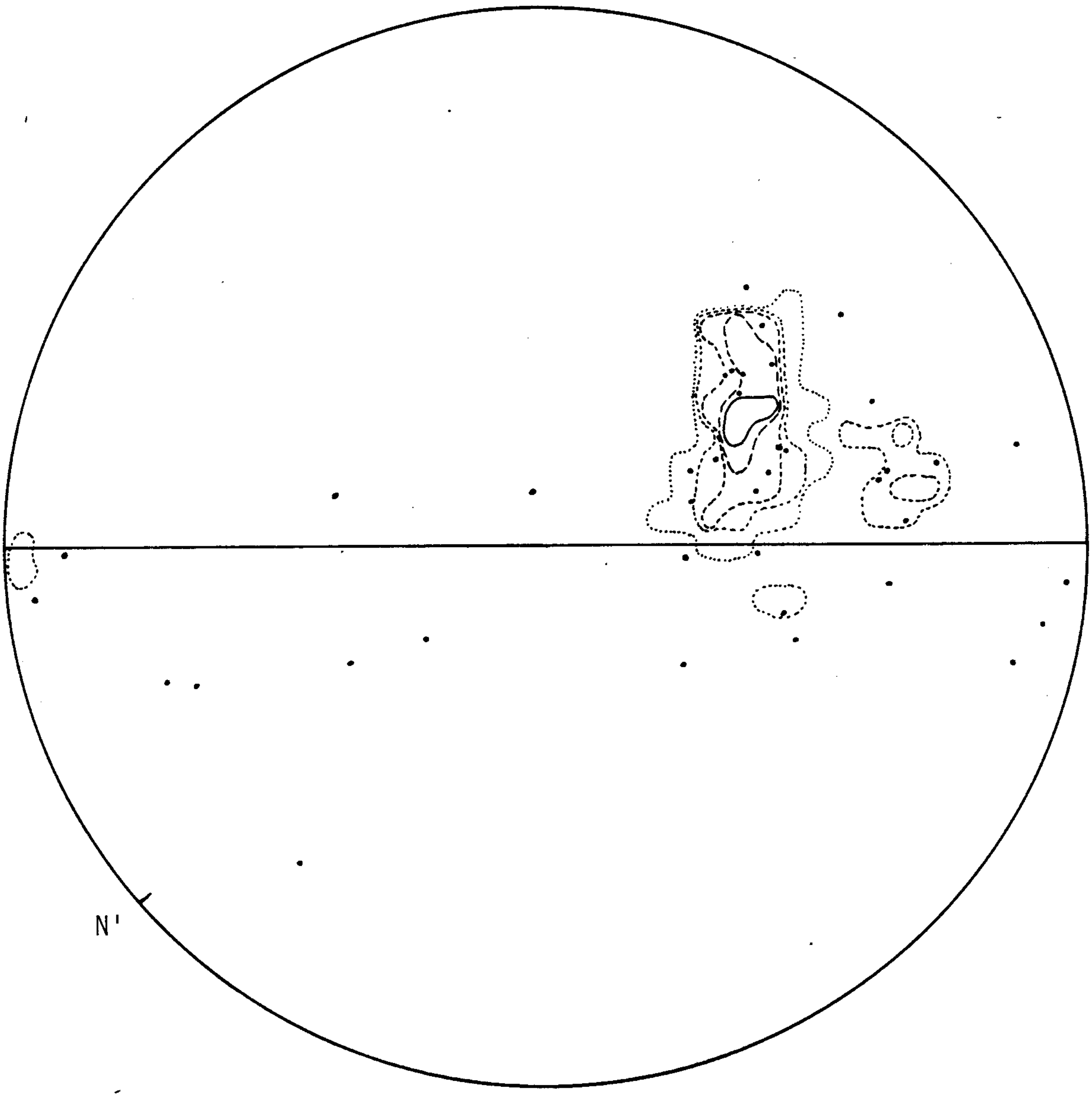
B-57 This sample was obtained from the middle of the upper harzburgites. It has a porphyroclastic texture and traces of "primary" clinopyroxene. The foliation has an attitude of N43E 50W. A sinistral shear sense is indicated. (42 measurements)

B-67 This rock was collected within the transition zone between the upper and lower harzburgites. As expected it shows porphyroclastic textures, but the enstatite grains have very little [001] elongation. The foliation attitude is N30E 37NW. A sinistral shear sense may be inferred. (50 measurements)

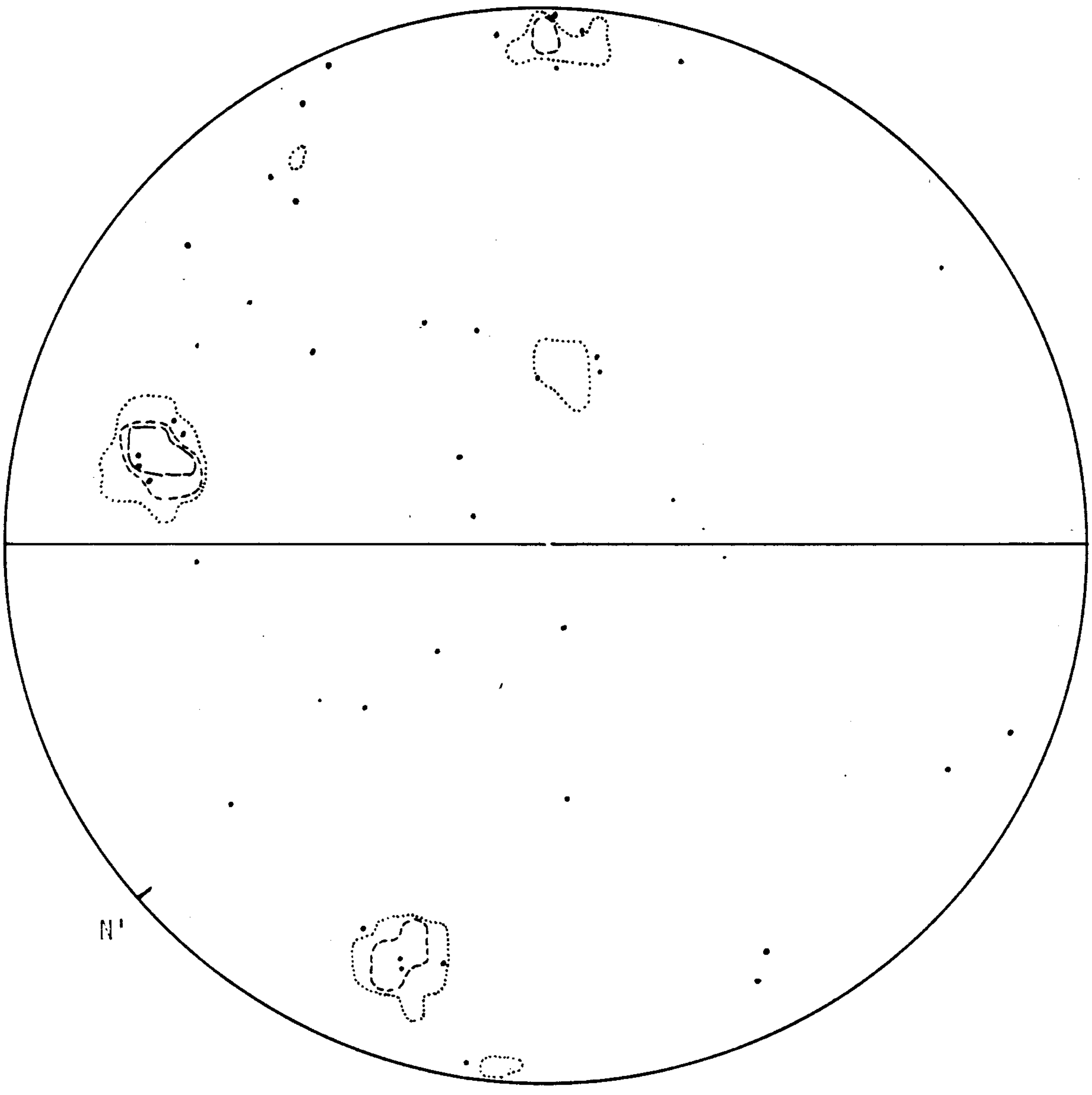
B-92 This rock was recovered from the head of Winter House Brook within the lower harzburgites. Its texture is typical of this unit. The foliation attitude is N42E 30NW. A sinistral shear sense is indicated. (42 measurements)



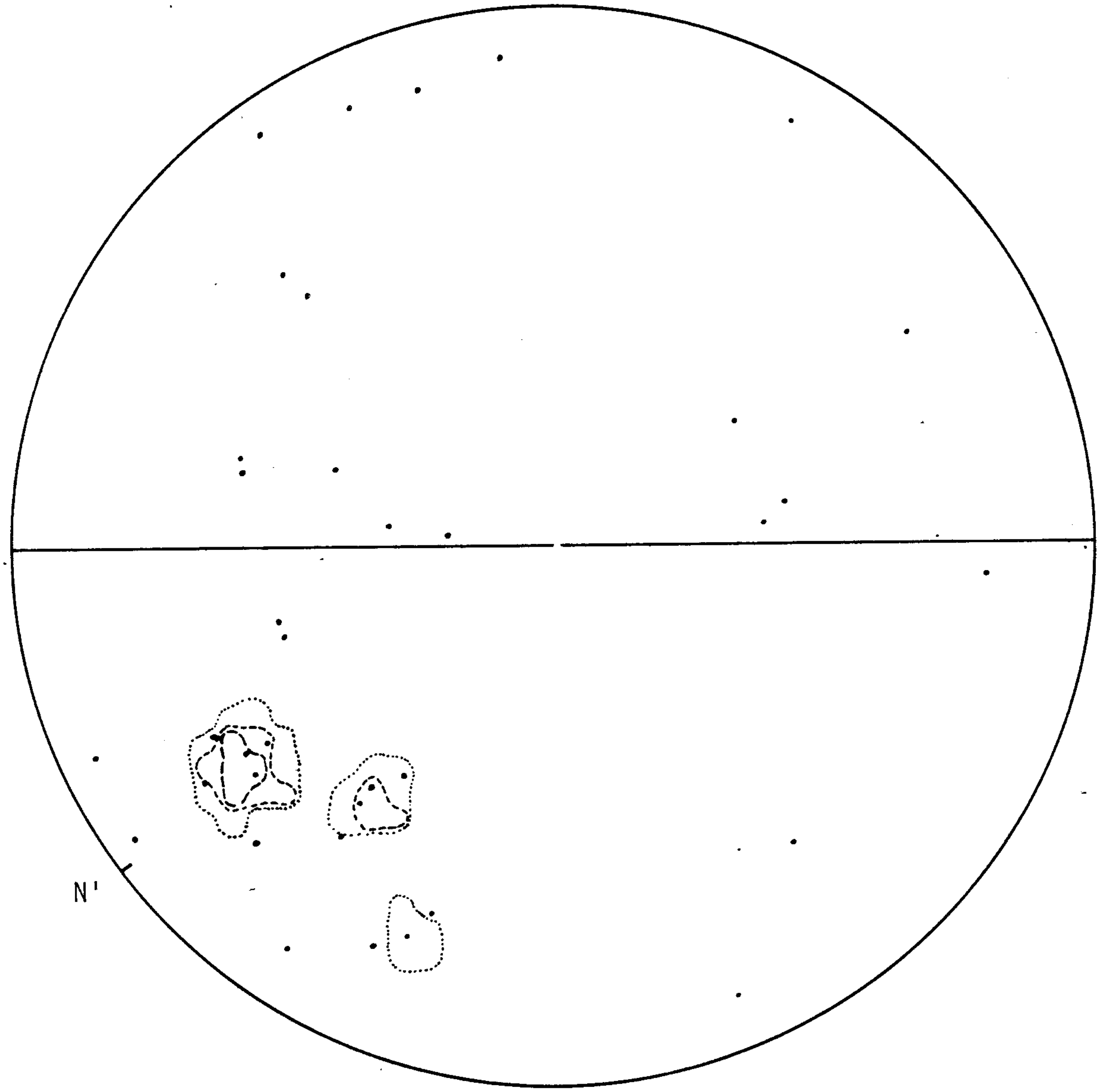
B34 [100]



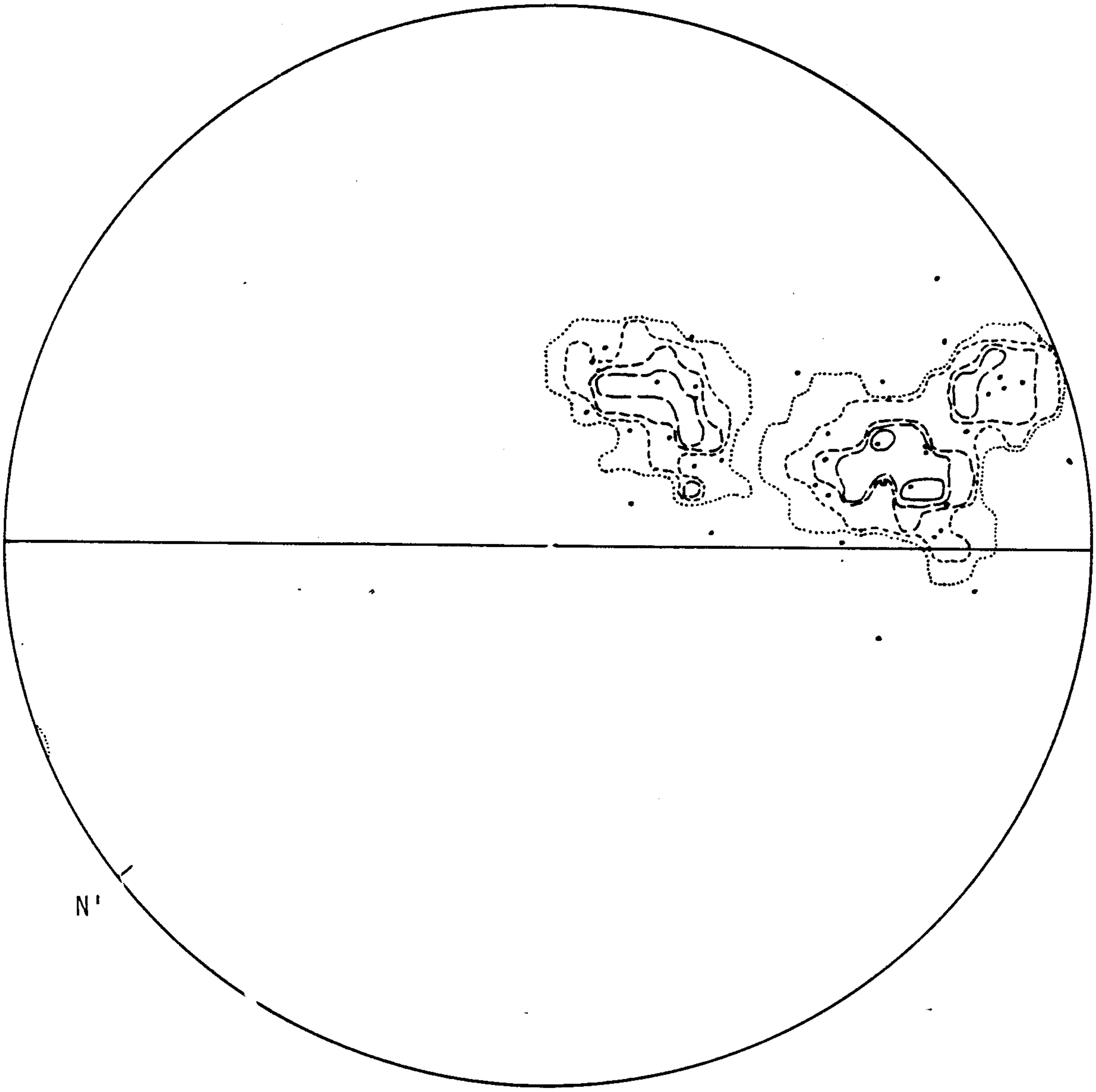
B57 [100]



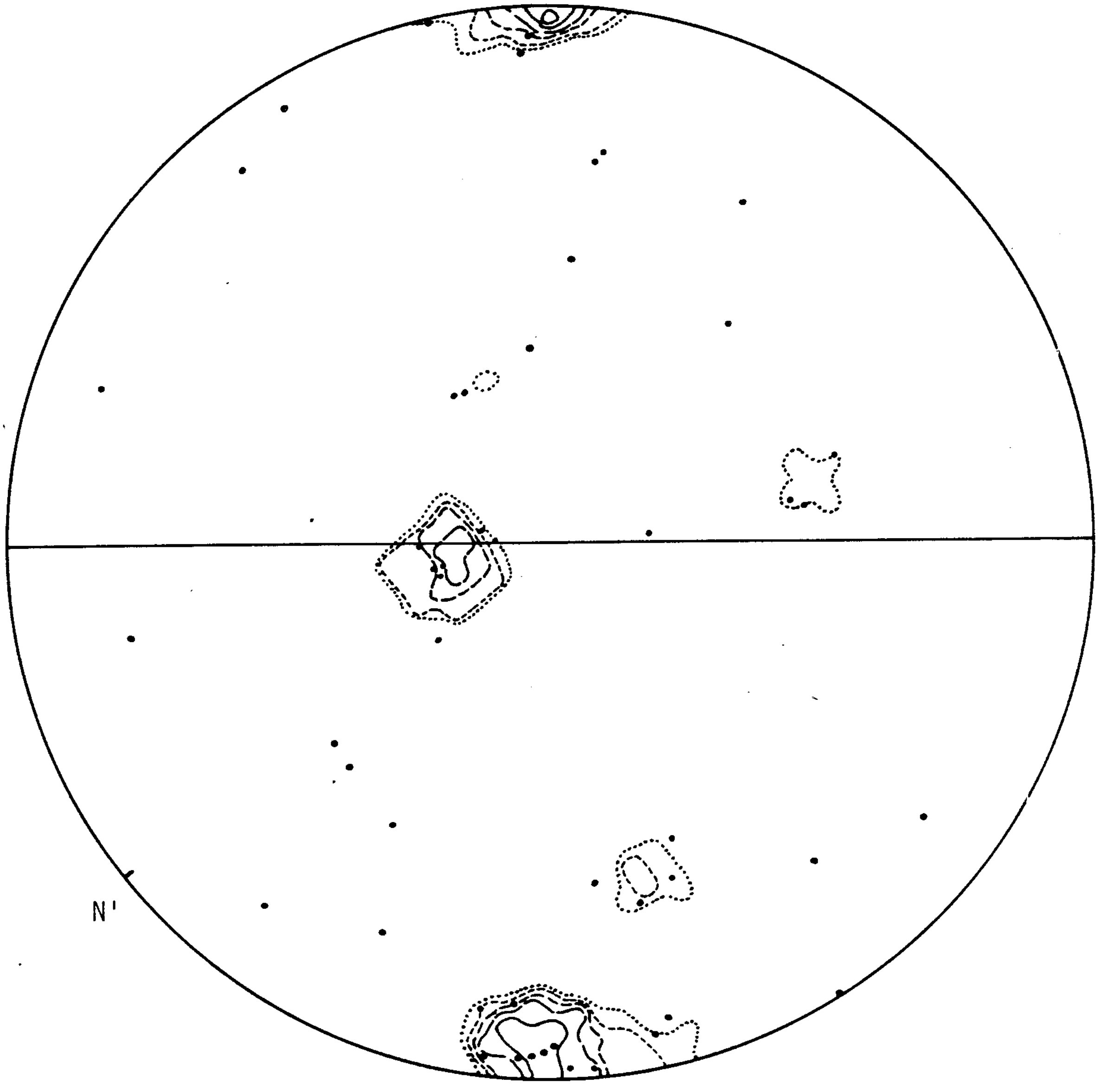
B57 [010]



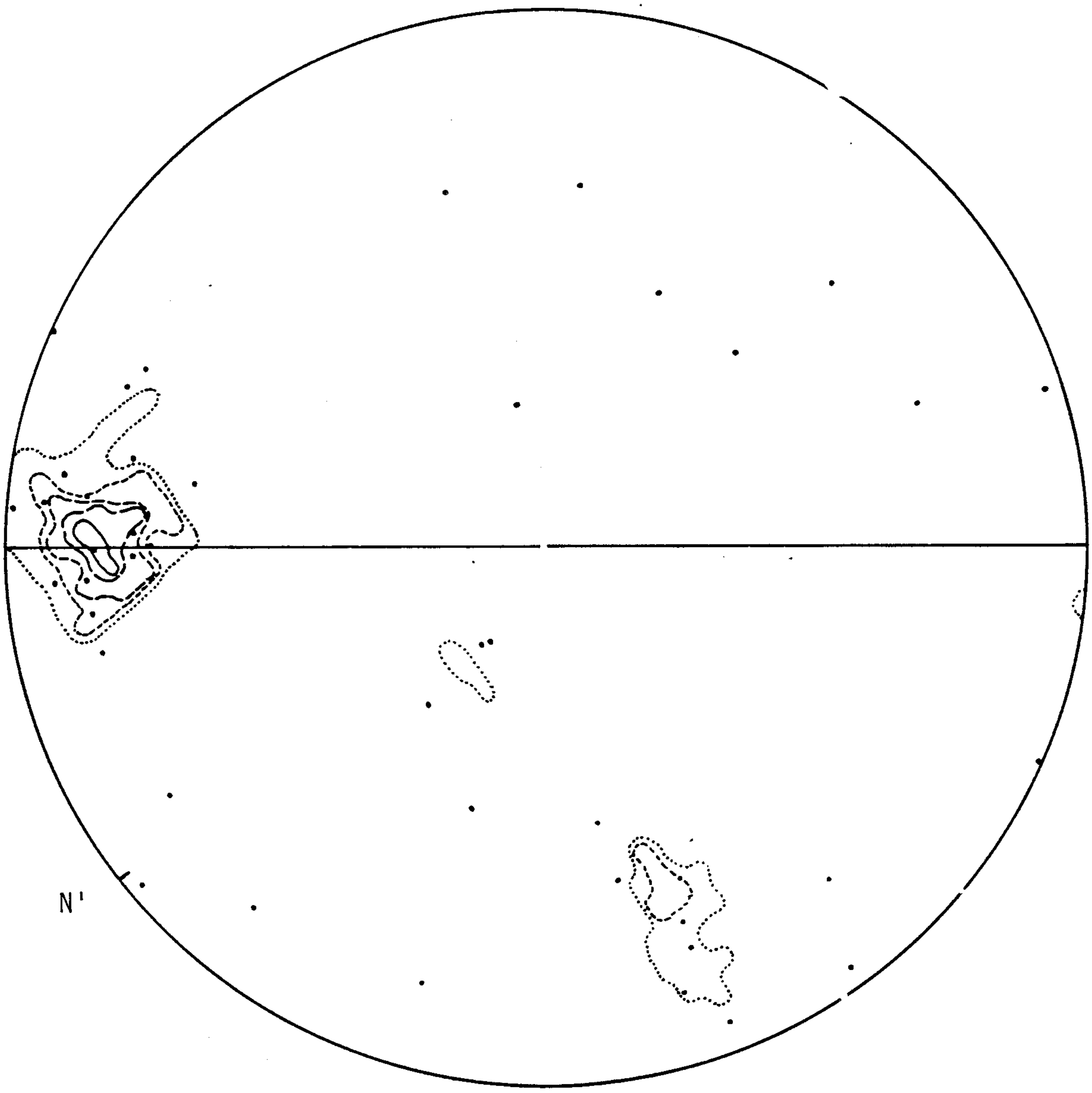
B57 [001]



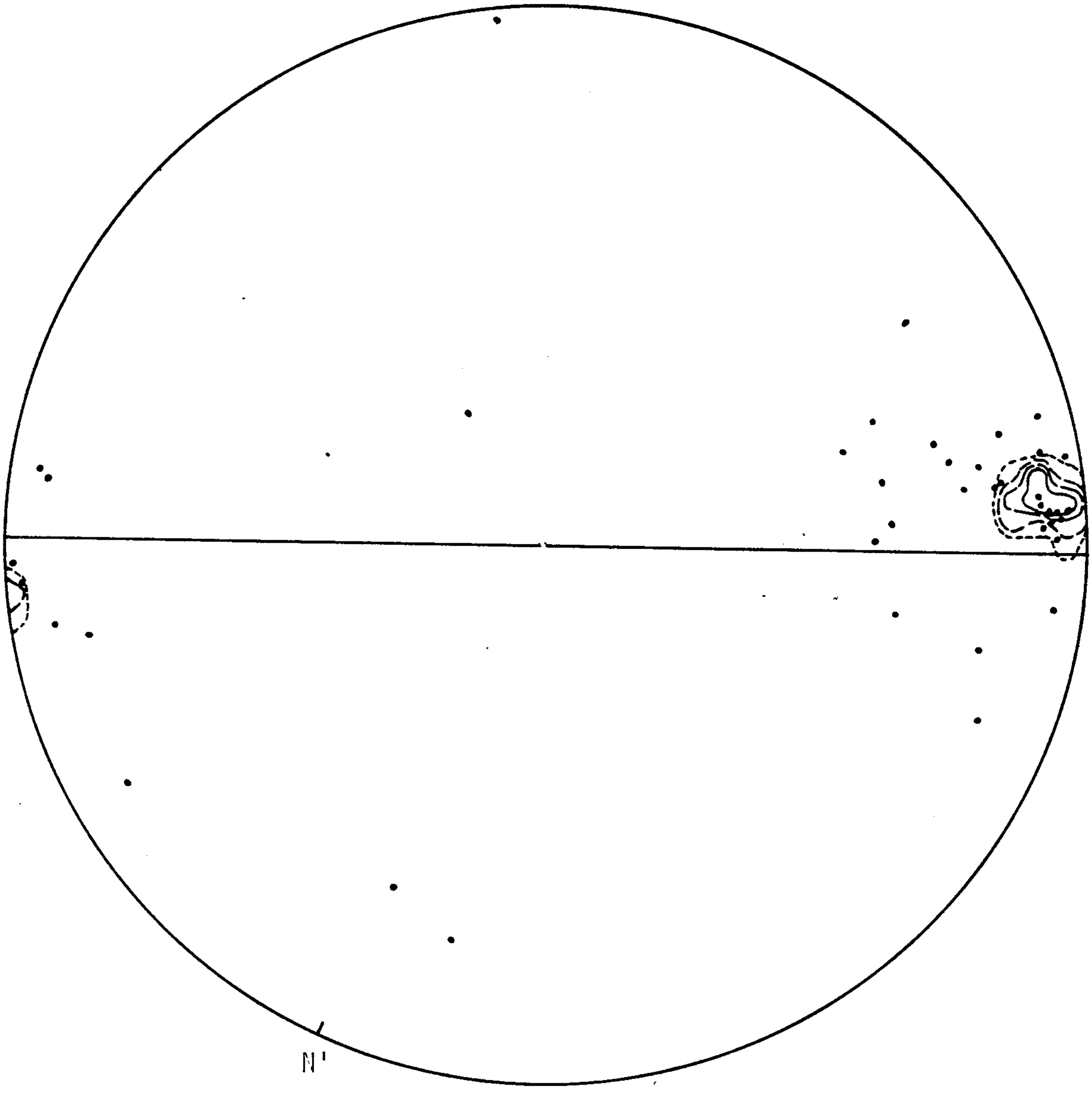
B67 [100]



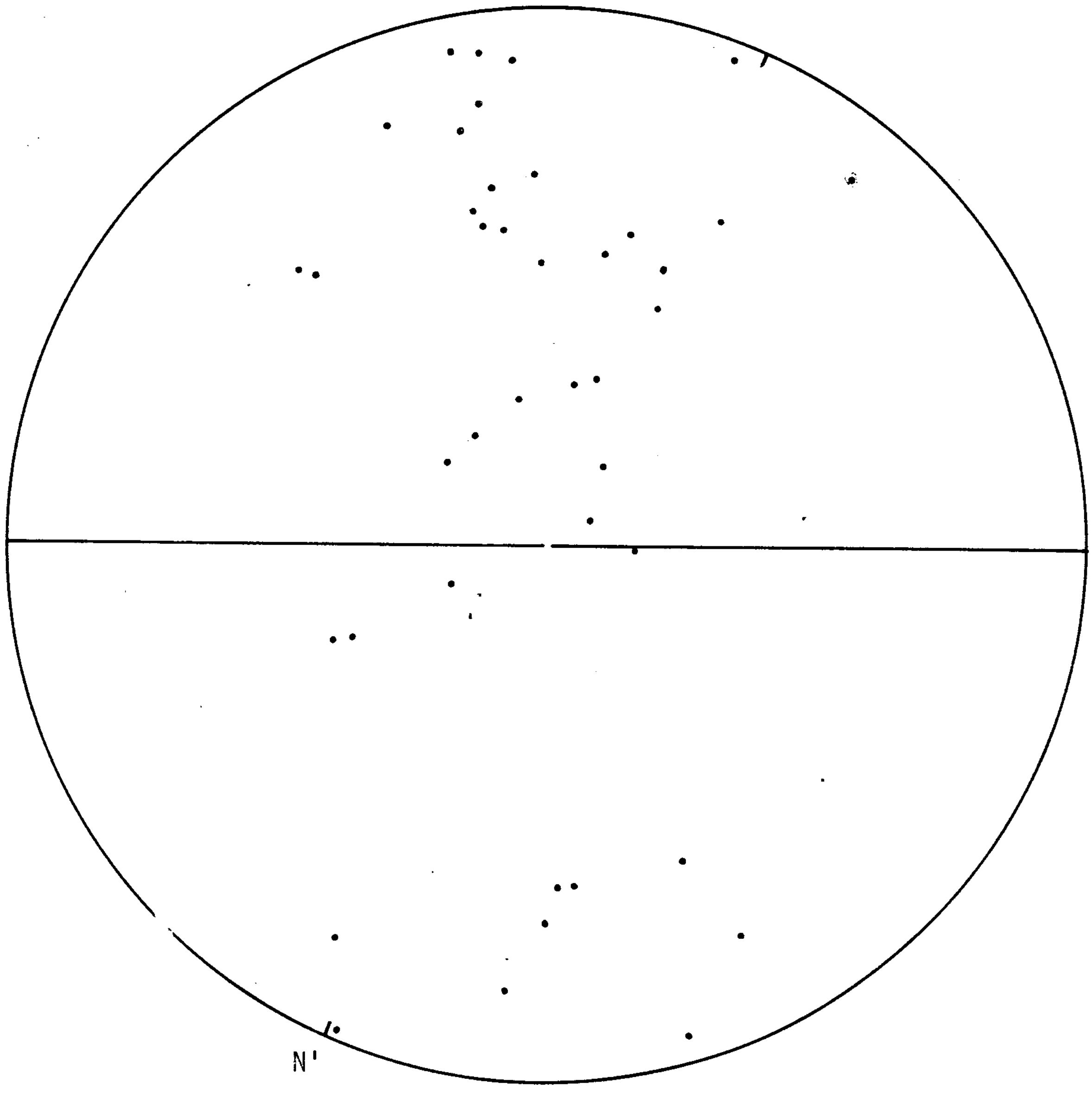
B67 [010]



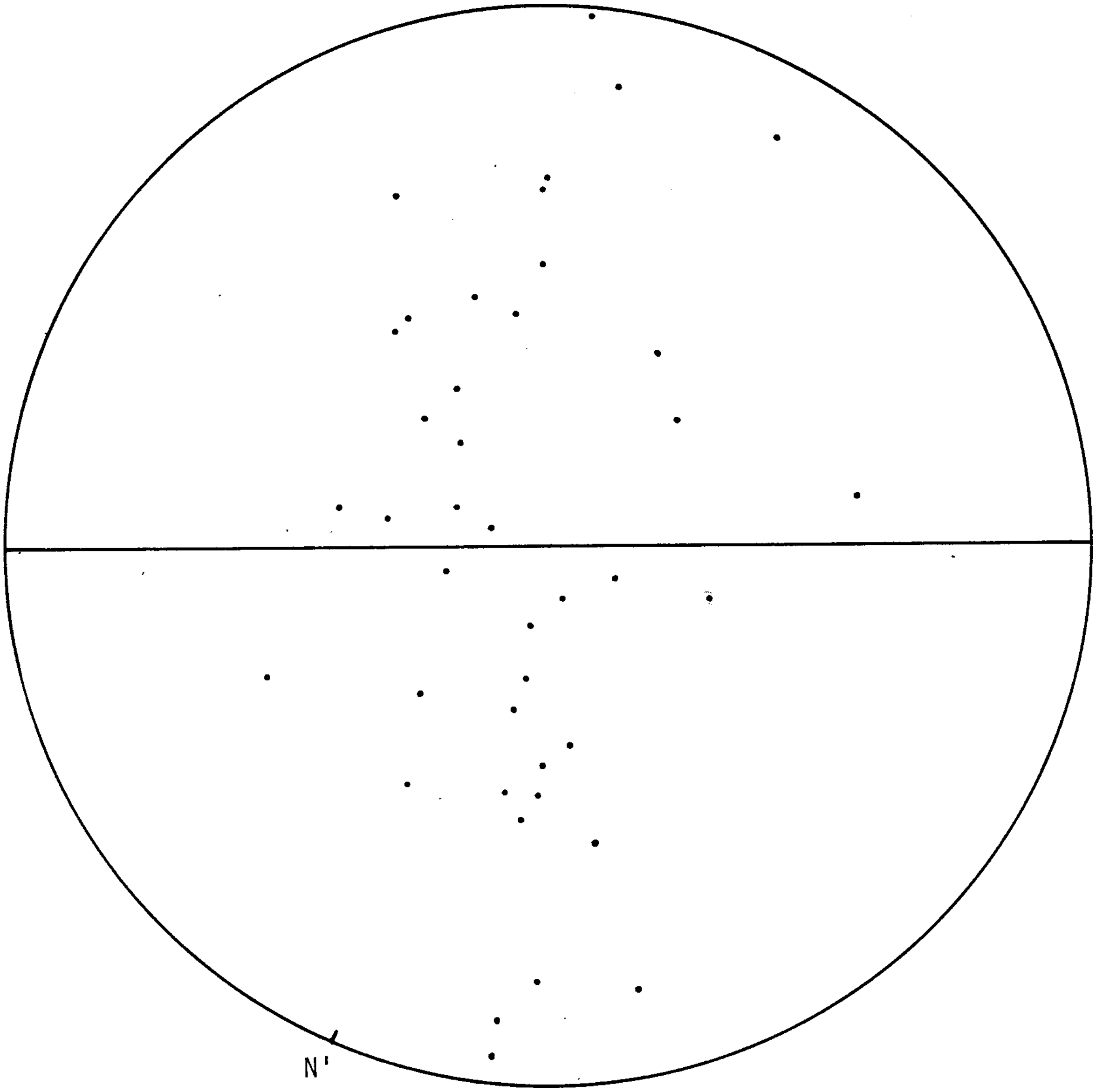
B67 [001]



B92 [100]



B92 [010]



B92 [001]

consistent with the observed "S" type fold vergence (axes N50-70W plunging 30-60°NW) (Plate A and O'Connell, 1979).

The dunite samples show much stronger $[100]_{01}$ fabrics than the overlying deformed cumulates. The one sample analyzed by Girardeau and Nicolas (1981) indicates a dextral sense of shear.

The olivine fabrics of the transitional harzburgites are slightly weaker than the dunite fabrics but significantly stronger than the deformed cumulates. Sample B-34 has a weak [100] maxima which is slightly oblique to the trace of the foliation, thereby indicating a sinistral shear sense. Again, this is consistent with the fold vergence data (four observations) from this portion of the northern face of Table Mountain.

Although the olivine fabrics in the harzburgites strengthen with depth away from the essentially flat-lying contact with the cumulates, the sense of shear inferred shows irregular inversions. Data from this research indicate that the upper and lower harzburgites generally show a sinistral sense of shear. Girardeau (1979) compiled a map of his sense of shear determinations in an attempt to distinguish large-scale zones which experienced a homogenous sense of shear. Although he identified three zones, his results were inconclusive because reversals constitute up to a quarter of the measurements comprising a single zone. One such apparent reversal is recorded by the structures near B-92 from the head of Winter House Brook. The $[100]_{01}$ maxima is oblique to the trace of the foliation and indicates a distinct sinistral sense. The fold vergence data gathered from both walls of the valley invariably show "S" type vergence although some "Z" type parasitic folds were noted on the limbs of large scale "S" type folds. The fold axes are approximately 50° oblique to the spinel lineation although their plunges are similar.

The outcrops from which samples giving dextral shear determinations were collected may often be in direct structural continuity with outcrops having structures indicative of sinistral shear. No evidence of ductile shear zones nor any disruption of penetrative structural elements was observed in the field, or in samples collected, along traverses through the harzburgite section. Sampling was not undertaken on a small enough scale to define the textural transition between units showing opposite shear sense. Girardeau's (1979) map of his sense of shear determinations clearly shows that reversal zones are very poorly defined and generally do not have extensive lateral continuity along the strike of the foliation.

In summary, the tectonized harzburgites exposed on Table Mountain are characterized by a consistent increase in the strength of the olivine fabrics at successively lower structural levels. With the exception of a zone of emplacement-related basal overprinting (Girardeau and Nicolas, 1981; Mercier, 1976), the sense of shear experienced by the harzburgite appears to be sinistral, although many areas give results of reverse sense. These zones which have experienced dextral shear appear to be volumetrically less significant but at present have very poorly defined lateral extent. The compositional layering is the oldest preserved penetrative structural texture in the tectonites and sense of shear reversals appear to occur along its strike. This, coupled with the structural and textural continuity of areas showing opposite shear sense, is compelling evidence that these shear domains formed during the earliest phase of the tectonite formation/evolution. They are most likely the result of complexities associated with axial zone upwelling and plating of residual material to opposite sides of diverging and subsiding lithosphere.

CHAPTER VI

MODELING OF OCEANIC RIDGE SYSTEMS

Introduction

Models of mid-ocean ridges have been proposed utilizing evidence from one or a combination of the following areas: seismic studies of oceanic crust and ridge axes (Rosendhal, 1976), bathymetric and oceanographic data (Moore _et al_, 1974; Cann, 1974), ophiolite structure and petrology (for example, Greenbaum, 1972; Dewey and Kidd, 1977; Juteau _et al_, 1977), and thermal constraints (Sleep, 1975; Nelson, 1980). The extensive variability of the proportions and juxtaposition of the hypabyssal and plutonic units of ophiolite suites has largely been explained by the examination of the intricacies of accretionary plate boundaries (Casey _et al_, 1981). Two major factors which lead to the heterogeneity of oceanic crust (hence variability in ridge dynamics) are proposed to be the offsetting of ridge segments by transform faults, and progressively changing spreading rates along a single ridge system. Through studies of magma petrology and structural associations of rock suites, two types of possible systems have been identified: (1) a single large steady-state magma chamber (Cann, 1974; Greenbaum, 1974; Dewey and Kidd, 1977, and (2) one with small, multiple chambers occurring at variable levels with non-steady-state magma supply (Moores and Vine, 1971; Smewing _et al_, 1975; Greenbaum, 1972). These are schematically shown in Figures VI-1.

The early models of magmatism along oceanic ridges largely favored magma chmabers with a triangular cross section (either flat-bottomed or flat-topped). Cann (1974) proposed the existence of a linear basaltic magma chamber at the base of the oceanic crust. He noted that with increased spreading rates the isotherms within the crust would be closer spaced, resulting in changes in proportion within the crustal suite but not necessarily in the overall thickness. An observation critical to his magma chamber profile was the "asymmetry" in structures on either side of the ridge crest. On a given side of the system the cumulate layering would always dip toward the ridge while the sheeted intrusives dip away from it. Cann also included a distinct flay lying contact between the crustal assemblage and the residual tectonized mantle because he argued that the dynamics of upwelling of partial melt between diverging plates should be a constant process.

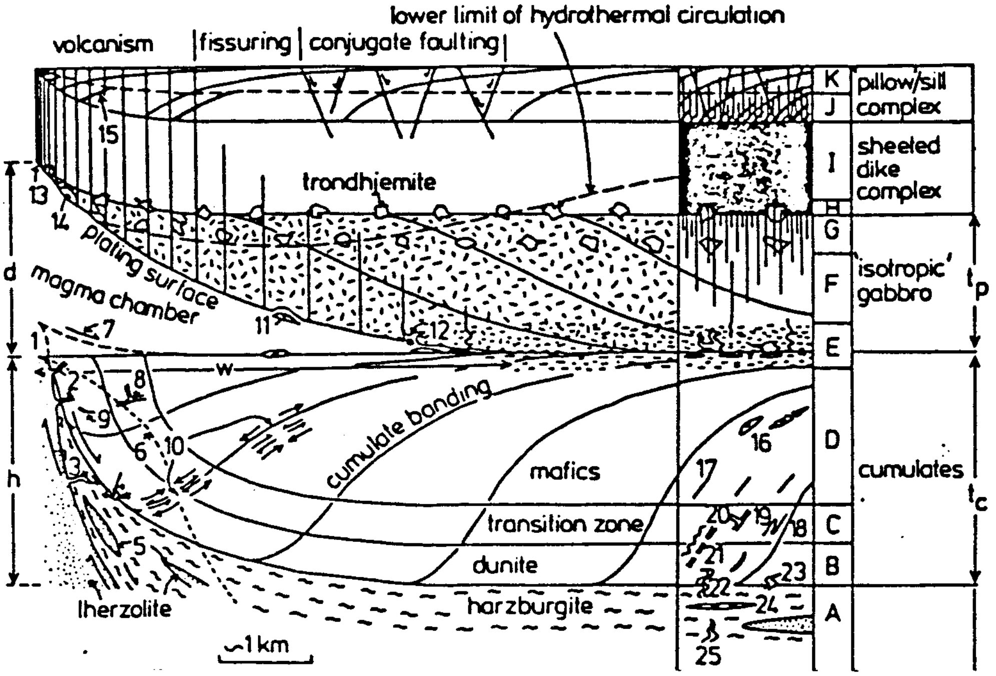
Sleep (1975) addressed the thermal modeling of a ridge system and concluded that a steady-state magma chamber could not exist along a ridge spreading at less than about one centimeter per year. The Bay of Islands Complex shows structures clearly indicative of formation at a fast spreading ridge (Casey, 1980; Karson, 1977; Dewey and Kidd, 1977). In light of this, a model for a single magma chamber will be presented.

Casey (1980) reviewed both the large steady-state magma chamber and the multiple pool models, comparing the geology expected from each with his observations at North Arm Mountain. The predicted random distribution of plutonic lithologies generated by small (1 to 2 km.) multiple magma chambers (Figure VI-1B) is not observed in any of the Bay of

Figure VI-1. Schematic diagram of magma chamber systems.

A) Proposed steady-state system with a single flat-bottomed magma chamber. The surface of the pillow lava suite is taken as the level datum surface assuming perfect isostatic compensation (from Dewey and Kidd, 1977).

B) The expected random distribution of lithologies within the plutonic suite of oceanic crust predicted by a multiple magma chamber system. (H = harzburgite, UM = ultramafic cumulates, TZ = transition zone, G = gabbros, Tr = quartz-rich differentiates). (from Casey, 1980).


lower limit of hydrothermal circulation
volcanism
fissuring
conjugate faulting
pillow/sill complex
sheeted dike complex
trondhjemite
plating surface
magma chamber
'isotropic' gabbro
cumulate banding
mafics
cumulates
transition zone
dunite
harzburgite
lherzolite
~1km
K
J
I
H
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C
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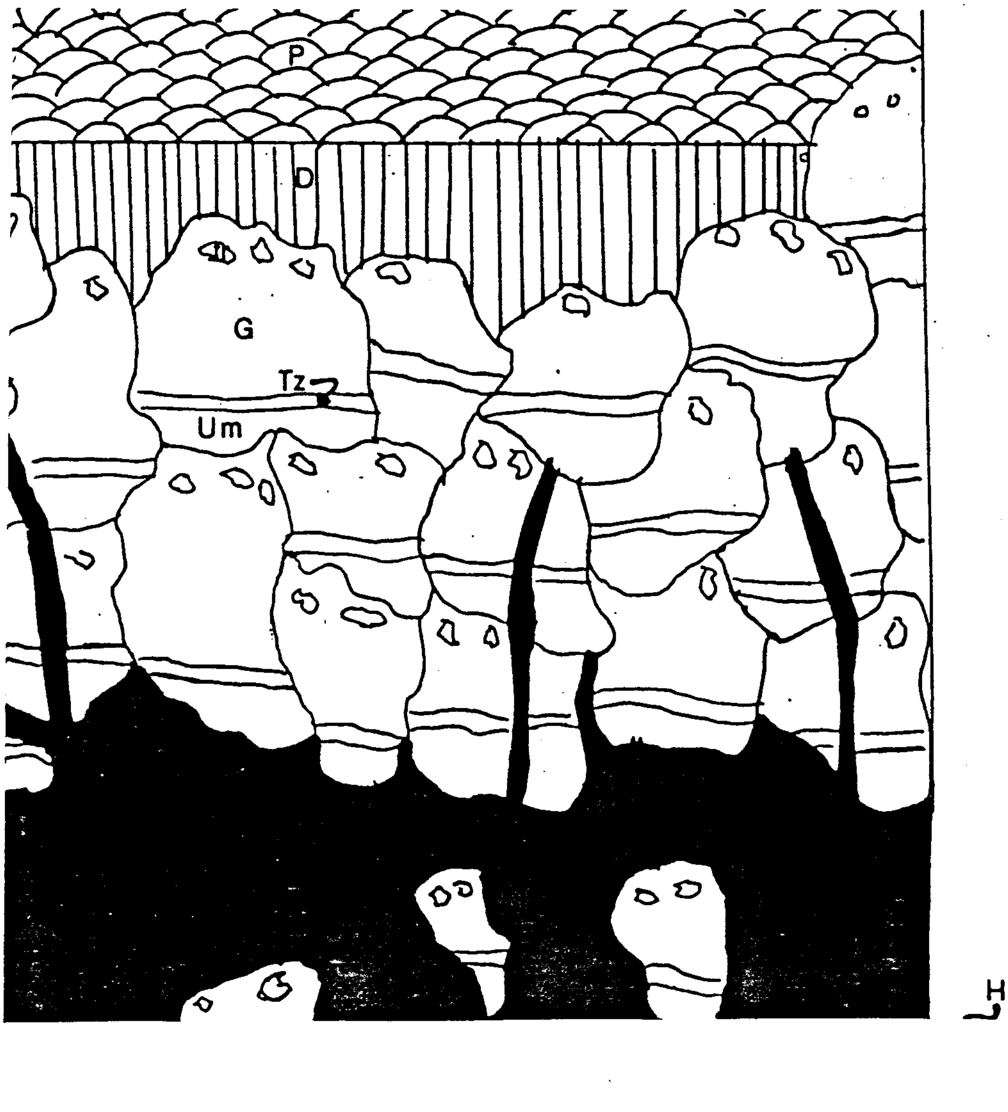

P
D
G
Tz
Um
H

Islands massifs. Instead, there is a complete and laterally continuous suite of harzburgite tectonites overlain by a mafic/ultramafic trasition zone, layered gabbros, with minor quartz-rich differentiates, and finally the intrusive and volcanic lid. This is compatible with a large, single magma chamber but not with any multiple chamber models (Dewey and Kidd, 1977).

A major argument for a single magma chamber of significant lateral extent is the absence of feeder dikes and sills in the layered and cumulate and lower isotropic gabbros (Dewey and Kidd, 1977). Dikes may be observed in the uppermost gabbros where underplating on the roof of the magma chamber would be expected. The existence of scarce dikes cutting through the basal plutonic units has been used by some to infer a lower magma chamber (Coleman, 1977). It is more likely that these are merely the result of the upward migration of minor melt trapped in the tectonite and transition zone (possibly concentrated by subsidence related deformation) or in near-transform environments where older crust will be resubjected to magmatic activity when it passes by the other ridge segment (Karson and Dewey, 1978).

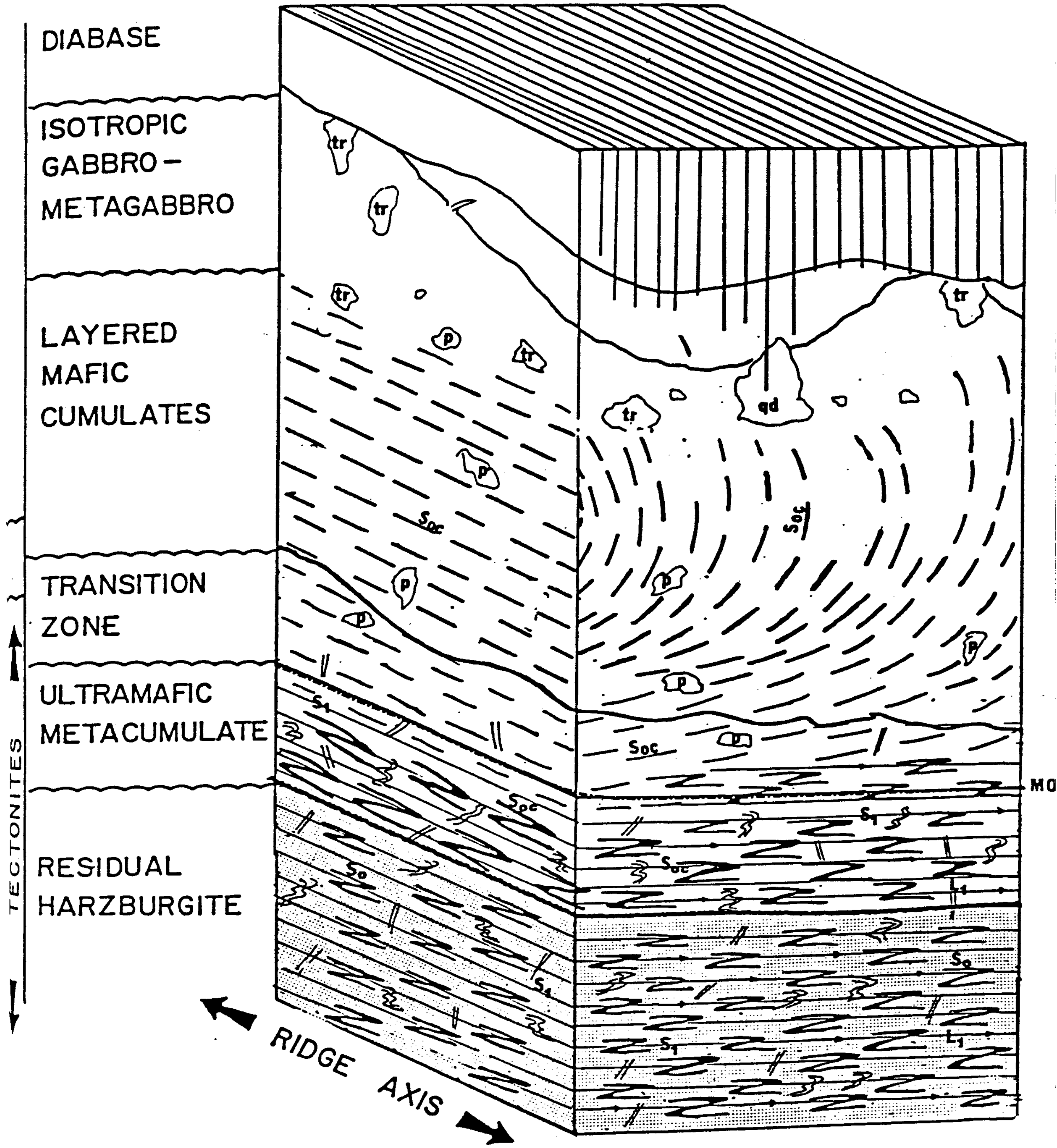
Previous objections to large steady-state magma chambers include the difficulty of obtaining lithologic stratification in a system which should be experiencing extensive convection, laterally discontinuous igeous layering (Allen, 1975; Greenbaum, 1972) and the support of a thin, wide volcanic and intrusive roof (Sleep, 1975). Casey clearly addressed and proposed solutions to the first two problems. As the rock suite of Table Mountain includes only the lowermost cumulates and tectonites, no further discussion will be given here. The reader is referred to Casey (1980), Rosencrantz (1980) and Nelson (1980).

Methods For Identifying Spreading Directions In Ophiolites

Inherent to the problem of fitting ridge models to the structural information derived from the study of ophiolites is the reconstruction of the orientation of the ophiolite massif relative to the ridge at which it formed. Where the upper volcanic and intrusive portions of the ophiolite are continuous with the lower portions, i.e. the cumulates and the residual tectonites, the overall trend of the sheeted dikes may be assumed to parallel the ridge axis. Kidd and Cann (1974) claimed that statistical analysis of one-way chilling directions may also indicate the side of the ridge on which the ophiolite formed. Recent arguments by Rosencrantz (1980) suggest that chilling statistics are not always reliable. He suggested that, as a result of rotation of the crustal lid down and away from the spreading axis, the volcanics tilt away from and dikes tilt toward the direction of spreading. Caution must be used, however, in assuming that dike trends parallel ridge systems, as trends are often deflected near oceanic fracture zones (for example, the Troodos/Arakapas Fault, Simonian and Gass, 1978; Bay of Islands Coastal Complex, Karson and Dewey, 1978). Paleohorizontal surfaces may be approximated by the large scale contact between the pillow lavas and the sheeted dikes, although the dips of individual flows will not yield valid information. A better marker is the gross contact between the cumulate suite (including the transitional dunites) and the tectonized harzburgite. There is a general consensus among workers examining ophiolites thought to have been generated by a steady-state magma system that the contact between the plutonic assemblage and the residual tectonites is flat-lying (e.g. Greenbaum, 1972; Cann, 1974; Dewey and Kidd, 1977; Casey and Karson, 1981). The cumulate layering is generally oblique to this contact and should either be concave toward the ridge axis, or if planar, dip toward it. Casey (1980) convincingly argued that the cumulate layering preserved in the layered gabbros represented progressively formed bounding margins of the magma chamber (Figure VI-2). The best control on the orientation of the parental ridge axis relative to an allochthonous massif occurs in those complexes with preserved fracture zone traces and relatively minor dismembering of the units by syn- or post tectonic faulting. Recent work by Fox, Gallo and others (in preparation) has shown that fissure and fault (inferred dike) trends along the East Pacific Rise are consistently parallel to the ridge axis until approximately 10 km from the intersection of the Tamayo Transform Fault with the ridge. The planar features then gradually swing toward the transform until along the flanks of the transform scarp they are nearly 45 degrees oblique to the ridge. The orientation of the transform and continuing fracture zone trace is always parallel to the net spreading of the ridge system (even in cases of oblique spreading).

The correct reorientation of a given ophiolite with respect to the parental ridge system is critical to testing the models of spreading systems. In many cases, however, apparently arbitrary decisions have been made. Ross <u>et al</u> (1980) presented a kinematic model for the

Figure VI-2. Reconstructed section for the North Arm Massif (also valid for Table Mountain) showing the arcuate patterns of igneous layering in relationship to sheeted dike orientation. Fold vergences are schematic; S_{oc} = igneous layering, S_0 = compositional layering in harzburgite, S_1 = foliation, L_1 = mineral or aggregate lineation (interpreted as elongation direction), P = pegmatities, Tr = trondjhemites, qd = quartz diorites. (From Casey, 1980).


DIABASE
ISOTROPIC GABBRO – METAGABBRO
LAYERED MAFIC CUMULATES
TRANSITION ZONE
ULTRAMAFIC METACUMULATE
RESIDUAL HARZBURGITE
TECTONITES
RIDGE AXIS
MO
tr
p
qd
Soc
So
S1
L1

Vourinos Complex of northern Greece, based largely on structural petrology and sense of shear determinations. Clear evidence was given for the approximate orientation of the principal flow direction (enstatite and spinel lineation trends) which may be correlated with the spreading direction in certain circumstances. The researchers gave no justification for the choice of which side of the spreading center the ophiolite formed at. The earlier work of Moores (1969) and Jackson et al. (1975) inferred an east-northeast trending ridge axis on the basis of sheeted dike orientation. As the block from which this data was obtained is completely fault bounded, the only plausible method of orienting the ophiolite with respect to its parent ridge involves the assumption that the principal elongation direction recorded in the tectonites is, indeed, normal to the ridge axis. From better preserved relationships observed within the Bay of Islands massifs, it becomes apparent that the S_1 foliation dips away from the ridge axis and that essentially consistent sense of shear determinations may indicate that structurally higher material moves away from the axis relative to the underlying material. Ross et al. (1980) have shown the opposite relationship in their model. If they had oriented the Vourinos body on the SSW side of their NNW/SSE trending ridge rather than on the opposing side, the structures would agree with the Bay of Islands Complex.

Relationship of Tectonite Fabric to Ridge Orientation

Experimental data on deformed dunites indicate that the preferred orientation of olivine is primarily due to plastic flow (intra-crystalline gliding). Nicolas (1972), Darot and Boudier (1975) and Juteau *et al*. (1977) all correlate spinel and enstatite lineations with the approximate orientation of the ductile flow direction that affected tectonized peridotites. Petrofabric data from the Bay of Islands Complex indicate that [100] (*a* axes) of olivine are sub-perpendicular to the sheeted dike directions while [010] (*b* axes) and [001] (*c* axes) lie within the plane of the sheeted dikes (Christensen and Salisbury, 1979).

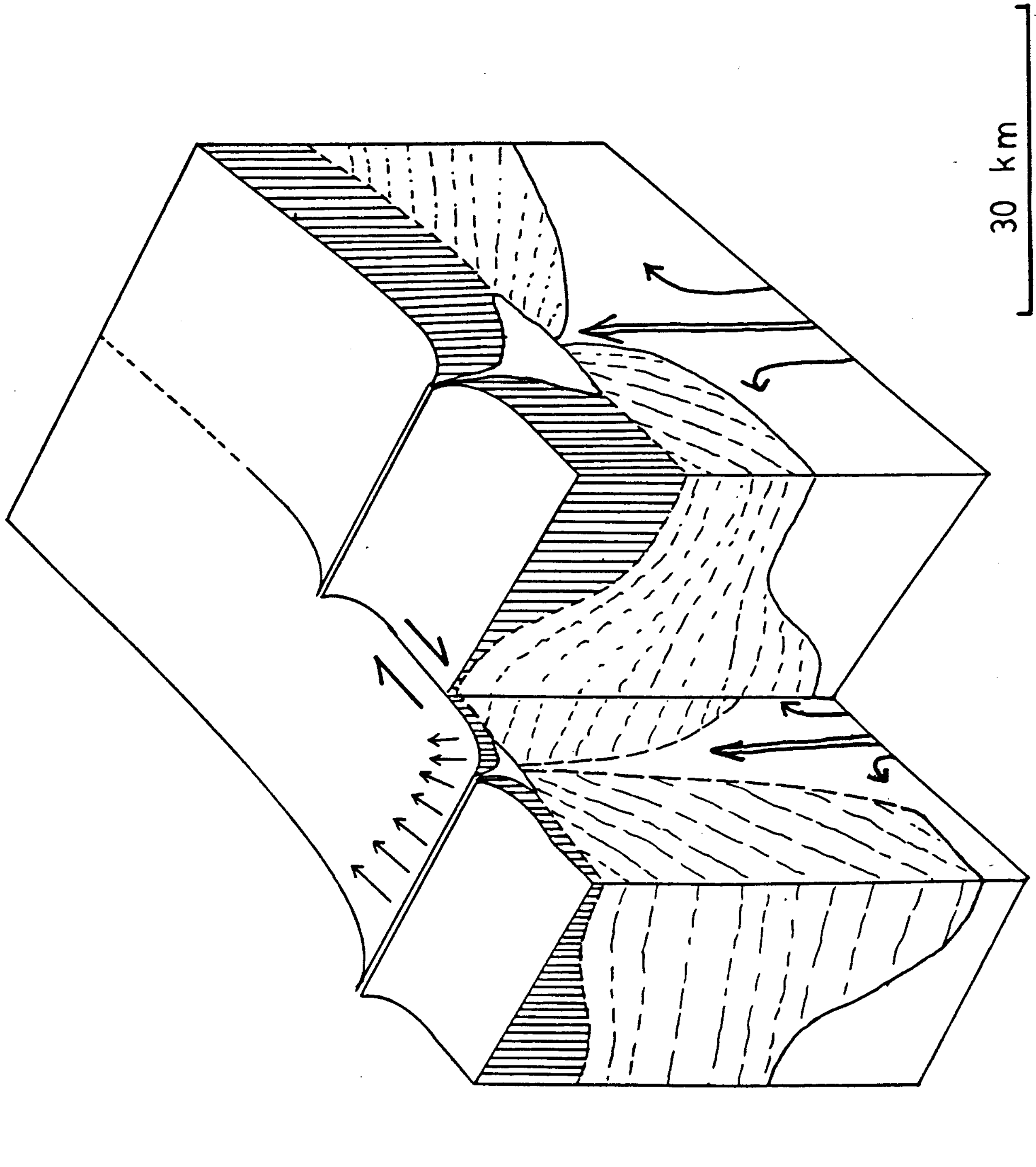
Submersible and bathymetric studies indicate that the topography associated with the fast spreading ridges changes on approach to transform segments. Magma chamber profiles would also be expected to change because the termination of magma chamber against colder, wet and thicker lithosphere would result in greater heat loss, and, perhaps, impaired melt supply to the system. The rate of separation of the two plates, however, would not change appreciably. Dynamical arguments would therefore suggest that the crust must thin as a result of impaired melt supply and geometrical requirement of maintenance of spreading rate. These observations suggest two complications which might alter the relationship between the ductile flow direction and the ridge axis:

1) Magma chambers narrow in lateral extent toward (and terminate) against) transform segments.

2) The juxtaposition of lithosphere of differing age and thickness might deflect the ductile flow gradient (i.e. the orientation of the principal elongation direction) in the same sense of shear as that of the transform segment. The older and thicker lithosphere will have a greater viscosity than the hot upwelling material and some viscous drag is bound to occur (see Figure VI-3).

From examination of the eastern intersection of the Tamayo Transform and the East Pacific Rise, Fox, Gallo, and others (in preparation) depict oblique normal faults and extensive "off-axis" volcanics occurring as much as 5 km away from the transform fault. Gallo and Fox propose a model requiring that oceanic crust thins and the lithosphere thickens towards the transform segments. They correlate the consistent deflection of fissures (dikes) and normal faults toward a transform segment with the deflection of the primary elongation direction affecting the crustal elements away from the transform segment. This relationship is depicted in Figure VI-3. The maximum observed deflection of the principal elongation direction is between 30 and 45 degrees. This strongly suggest that the plastic flow direction in the upper mantle is also deflected. In fact, olivine [100] maxima from Table Mountain and North Arm Mountain show 10 and 20 degrees dextral deflections if a NW/SE ridge orientation is assumed. The distance from a ridge/transform intersection to the point where the deflection of the principal elongation axis begins is a function

Figure VI-3. Block diagram denoting Gallo's (in preparation) model requiring the thinning of crust and thickening of lithosphere toward a transform segment. Magma chamber profiles have been drawn to approximate scale. Vertical solid lines = oceanic crust separated by ridge system. Irregularly dashed lines = traces of S_1 foliation. Heavy arrows beneath ridge indicate possible flow gradient and axial zone of upwelling.


30 km

of the magnitude of the transform offset and of spreading rate. In general, the greater the spreading rate, the closer to the transform/ ridge intersection is the deflection. On the other hand, the deflection distance increases with the magnitude of the transform offset.

Yet another area which may aid in the determination of a paleo-ridge orientation is seismic anisotropy research. $[100]_{ol}$ is the fast direction for the propagation of compressional waves. Fox (personal communication) feels that the resolution of this technique is good only for the crustal suite. There is some ambiguity in the interpretation of values along the top of the Moho. None the less, laboratory petrofabric analysis of peridotite samples collected from ophiolites does agree with inferred anisotropy from seismic refraction data. (Christensen and Salisbury, 1979).

The orientations of the paleo-ridge axis proposed for the Bay Islands Complex vary by nearly 90 degrees. A majority of the papers favor a ridge with a NW/SE orientation based on the average sheeted dike orientation on North Arm Mountain, Blow-Me-Down Mountain and Lewis Hills (Dewey and Kidd, 1977; Christensen and Salisbury, 1979; Karson and Dewey, 1978; Casey and Karson, 1981; Rosencrantz, 1981). However, Girardeau and Nicolas (1981) favor a NE/SW ridge orientation based on enstatite and spinel lineations. The techniques discussed in the preceeding paragraphs have been applied to the various massifs within the Bay of Islands. The results are shown in Table VI-1. It is critical to note that North Arm Mountain is a close synformal structure

ORIENTATION OF PALEO-RIDGE AXIAL DIRECTIONS FOR THE BAY OF ISLANDS MASSIFS

METHOD		INFERRED RIDGE ORIENTATION
Orientation of sheeted dikes:		
North Arm Mountain[1]	N45W (one-way chilling data, NE side)	NW/SE (nearly vertical)
Blow Me Down Mountain[2]	N50W	N50W
Lewis Hills[3]	NW to NNW (if the massif is rotated to align the fracture zone trace, dikes then N to NNE)	*
Fracture zone trace:		
Mt. Barren Assemblage - Coastal Complex reconstructed orientation N30E NE side of system inferred on the basis of structural data.[4]		N60W
Olivine fabrics ($[100]_{ol}$ approximately perpendicular to ridge axis):		
Table Mountain[5,6]	$[100]_{ol}$ N55E	N35W
North Arm Mountain		
Blow Me Down Mountain[5,7]	$[100]_{ol}$ N60E	N30W
Lewis Hills		
Spinel and enstatite lineations:		
Table Mountain[5]	N15W	
North Arm Mountain	N25W	
Blow Me Down Mountain[5]	N45W	NE/SW[5]
Lewis Hills		

[1]Casey, 1980; Rosencrantz, 1980. [2]Williams and Malpas, 1972. [3]Karson, 1977. [4]Karson and Dewey, 1978. [5]Girardeau and Nicolas, 1981. [6]Christensen and Salisbury, 1979. [7]Mercier, 1976 a.

* inferred orientation not given because, in both the Troodos Ophiolite and along the transform, dike orientation clearly swings toward the transform.

and Table Mountain is an open synformal structure and that rotations of the fabric data generally do not account for this.

Despite the compelling evidence relating enstatite and spinel lineations to the ductile flow direction, it is unwise to disregard all other lines of evidence which consistently support a NW/SE ridge orientation. In fact, spreading directions do not necessarily parallel the normal to ridge axis. The work of Gallo and others on the Tamayo Transofrm indicates that the principal elongation direction (the long axis of the strain ellipse) begins to become deflected away from the transform fault perhaps as much as 10 km away from the fracture zone. Although the features which Gallo based his model on are strictly limited to the crustal domain, a progressive swing in the spinel and enstatite lineations within the upper mantle adjacent to fracture zone traces is also plausible. Further work on ophiolites with preserved fracture zone assemblages will be required in order to substantiate this. As crustal dynamics is far better constrained than upper mantle processes, it seems prudent to assume a NW/SE ridge orientation when modeling the Bay of Islands Complex.

Geophysical and Rheological Considerations

Upper mantle rheology constrains the mechanisms responsible for feeding the magma chamber and for the response of the upper mantle to the diverging and subsiding oceanic crust. Research in this area has produced estimates of the deviatoric stress, strain rate and viscosity as functions of depth. Recrystallized grain size paleopiezometry has been revised and utilized in conjunction with single pyroxene thermobarometry to give deviatoric stress estimates (Avé Lallemant et al, 1980). Using experimentally/theoretically determined flow laws and reequilibration paths calculated through thermobarometry, estimates of the strain rate affecting mantle tectonites have also been made (Ross et al, 1980). Cathles (1975) and Twiss (1976) addressed the question of mantle viscosity, relating it to depth and strain rate. These factors clearly control the diapirism or upwelling of mantle beneath oceanic ridges and must be compatible with the values predicted by any proposed ridge models.

Ave Lallemant et al. (1980) calculated differential stresses from intracratonic peridotite xenoliths, observing a general decrease in deviatoric stress from 200 bars at 50 km to 40 bars at 80 km with an increase around 70 km. Similar reversals were observed in suites of xenoliths collected from other continents, although the depth of the reversal was variable. The workers note that the strain rate shows a slight increase with depth (10^{-17} to 10^{-15} overall range) while the viscosity decreased with depth (10^{24} to 10^{22} poise range). Similar inversions in the general trend of a decrease in the deviatoric stress with depth were reported by Nicolas, Boudier and Bouchez (1979), in a study of over twenty ophiolites with well preserved mantle tectonite suites. These researchers concluded that both differential stress and strain initially decrease with depth and then show a rapid increase in the basal zone of the complexes. The textures in these basal suites grade from porphyroclastic to mylonitic and result from an overprinting of obduction related conditions on the pre-existing ridge generated system. The inversions observed in the sub-continental mantle cannot be explained by obduction overprinting and will not be addressed here.

A narrow axial zone of upwelling is supported by the quantitative geophysical, geochemical and petrological modeling of submarine lithologies conducted by Bottinga and Steinmetz (1979). This work also led to a prediction of partial melt distribution in the upper mantle near the ridge axes. Three to eight weight percent partial melt may occur in a lenticular zone at 15 to 25 km depth and approximately 15 to 30 km away from the ridge axial plane. As a consequence, the occurrence of a "secondary" lherzolite may be postulated. The interlayered harzburgite and lherzolite discovered at an approximate depth of 7 to 8 km within the harzburgites of Table Mountain does appear to be the result of the crystallization of melt trapped within a residual host rock (see Chapter V). The limited extent of exposure of these lherzolites is problematic and cannot be explained without further detailed mapping and chemical analysis.

Evidence of Tectonic Shortening

Mercier (1976 a, b) calculated temperature and pressure gradients for the tectonized harzburgites and lherzolites collected from the Bay of Islands Complex. The maximum depths inferred from his single pyroxene geobarometry and geothermometry are between 100 and 120 km for the sheared lherzolites associated with the basal aureole, 60 km for the lower harzburgites and 50 km for the upper harzburgites. This was the basis for Mercier's proposed obduction mechanism which required huge amounts of tectonic shortening during obduction.

General observations cast serious doubt on this. In the field, the distinct lack of late ductile shear zones (i.e. those crosscutting the orthopyroxenite and dunite dikes) west of Winter House Brook (Plate A) agrues against substantial shortening of this portion of the section. Shear zones were observed in the lower harzburgites, but no structural evidence of substantial shortening was observed in the field. Even if substantial shortening did occur along these zones, it only affected the bottom 3 km of the Table Mountain suite.

Furthermore, recent work by Dewey (personal communication) indicates that the thickness of obducted slabs depends upon the age of the crust as obduction is basically the flaking off of the most brittle portion (i.e. the tectosphere) from the more plastic lithosphere. Dewey notes that the 650° isotherm closely approximates the boundary of the tectosphere. If 25 ma. elapsed before obduction mechanisms affected the Bay of Islands Complex, the flake likely to separate off would have been only 15 to 18 km thick. The actual reconstructed thickness of the Bay of Islands ophiolite is variable but reaches 15 km (Dewey and Kidd, 1977; Casey, 1980). Material at 50 to 120 km depth would be completely ductile at the time obduction commenced and would tend to flow rather than be broken off. Obduction would then involve only the elastic portions of the crust and upper mantle with deformation restricted only to a narrow basal zone of the thrust sheet. This leaves a discrepancy of 50 km between Mercier's single pyroxene geobarometry and the apparent structural completeness/continuity of the upper harzburgites. This may be the result of reequilibration or possibly a modeling error.

Discussion

Within those intact ophiolite suites thought to have formed along a fast spreading ridge with a single steady-state magma chamber (e.g. Bay of Islands, Semail, Troodos, and Trinity) the following structures are commonly observed:

1) Penetrative high temperature deformation fabrics extend upwards from the residual harzburgite 100 to 500 meters into the basal clinopyroxene and plagioclase-bearing cumulates (Dewey and Kidd, 1977; Moores, 1969; George, 1978; and this thesis).
2) Highly deformed dunite bodies ranging up to 300 meters thick and 5 kilometers in lateral extent occur between the plagioclase bearing cumulates and the harzburgites. These rarely show relict cumulate textures and have a gradational contact with the harzburgite yet a sharp contact with the deformed cumulates (Girardeau, 1979; George, 1978; Quick, in press, and this thesis).
3) Variably deformed pyroxenite and dunite dikes crosscut the uppermost harzburgites and the dunites but rarely, if ever, extend into units higher than the transition zone cumulates (Dewey and Kidd, 1977; Karson, 1977; and this paper).

4) This study reveals a fanning of the S_1 foliation and the spinel and enstatite lineations within the harzburgites. The olivine [100] maxima may also swing away from fracture zone traces.

5) Within a plane cut perpendicular to the ridge axis the same sense of shear is expereienced by the lower deformed cumulates and upper harzburgites. To the right of the axial plane, this sense is dextral and to the left, it is sinistral (Figure VI-4). Minor zones with the reverse shear sense are to be expected.

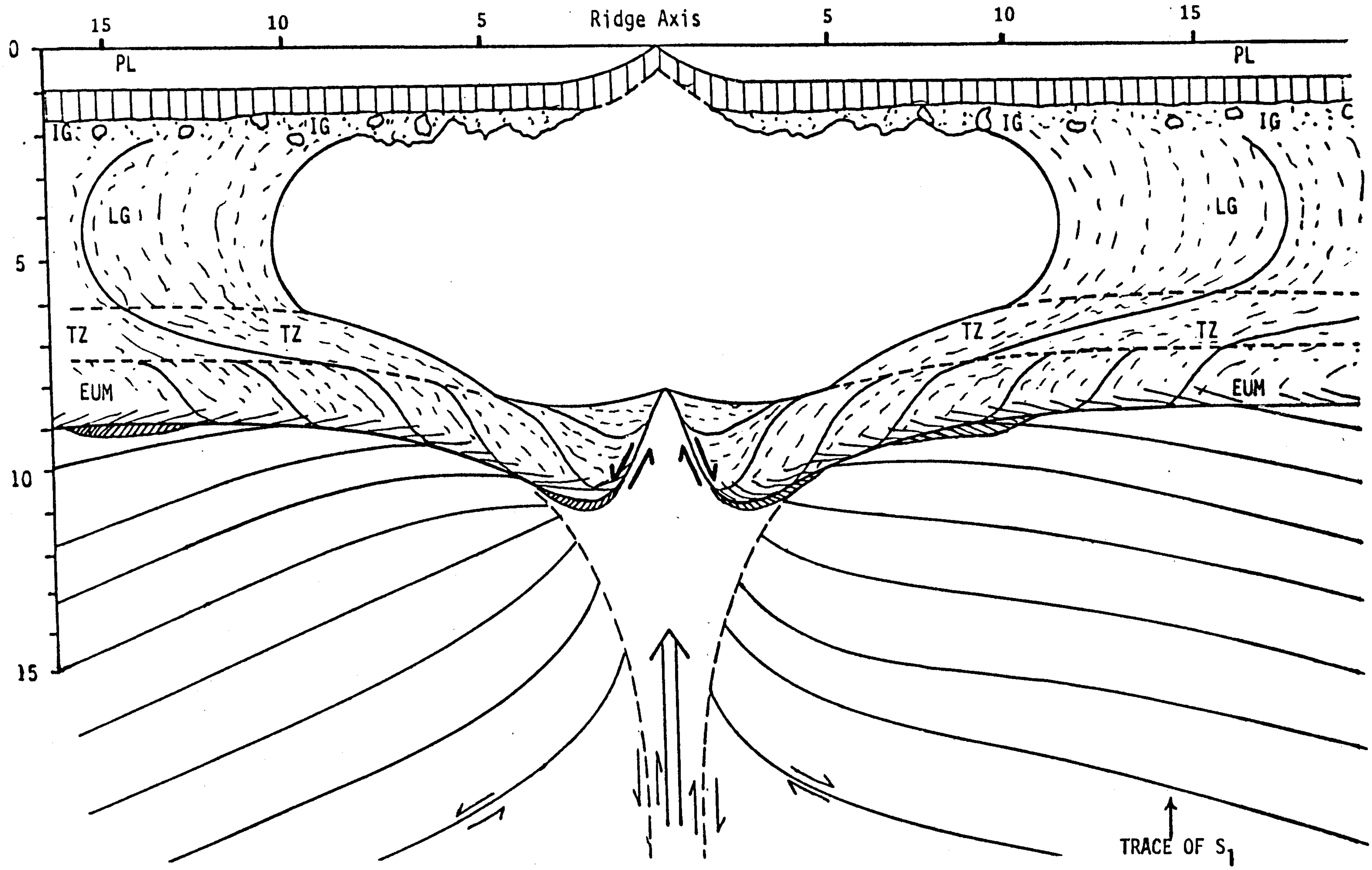
The ridge magma chamber model which is here proposed as best describing the structures observed in the Bay of Islands Complex is largely a synthesis of the models proposed by Dewey and Kidd (1977) and Casey (1980). The relationship between the foliation and lineation in the harzburgites and the penetrative deformation affecting the lower cumulates is best explained if the foliation dips away from the ridge axis rather than toward it as has been previously proposed by Juteau et al. (1977). With an essentially flat-bottomed chamber which would allow a shear couple between the harzburgite and the cumulate pile, the penetrative deformation affecting the basal cumulates could easily be concordant with that in the residual tectonites (Figure VI-4).

Casey's magma chamber profile clearly explains the attitudes of the layering in the underformed gabbros and the layered cumulates (Figure VI-2). Support of a wide, thin magma chamber roof has been examined by Rosencrantz (1980) and Nelson (1980) and is not necessarily a mechanical or dynamic problem for large magma chambers. The density contrast between the crust and magma coupled with the required rate of heat loss (hence convection within the magma chamber) both requires and supports a thin crustal carapace. However, the steeply dipping and narrow, tapering base of Casey's model does not explain the observed structures in the basal cumulates.

The mechanism of _in situ_ nucleation and crystal growth on the bounding surfaces of a magma chamber beautifully explains many of the incongruous textures and structures commonly observed in the basal cumulate suites of ophiolites. Some magmatic sedimentation may be involved as well, with apparent channel structures and cross-bedding developed as the result of the circulation of crystal/melt mixtures. Jackson (1971) examined the settling velocities of cumulus phases within a melt. Using Stoke's Law he calculated settling rates of 10 to 100 meters/year for very fine grained chromite and feldspar grains and 100's to 1000's of meters/year for coarser grained chromites, olivines and pyroxenes. These rates are so extreme that the circulation resulting from convection will not easily counteract the settling. The narrow base of Casey's profile could conceivably concentrate some of the settling phases. It would also be likely that a change in concentration of cumulus phases would occur with the change in slope of the margins of the chamber. Within the Bay of Islands cumulate sections, chromite is sparsely but evenly distributed throughout the section although olivine is concentrated toward the base of the cumulates, therefore giving an ambiguous relationship with regard to settling models.

The large tabular dunite bodies sandwiched between the base of the cumulate suite and the residual harzburgites in Table Mountain as well

Figure VI-4. Diagrammatic cross-section of proposed spreading ridge system. The upper portion of the magma chamber profile (through the transition zone) has been adapted from Casey (1980). The base of the chamber and axial zone interface of cumulate and tectonized residual material has been modified after Dewey and Kidd (1977). The heavy lines curving through the layered gabbros (LG), the transition zone (TZ), and the enstatite-free ultramafic cumulates (EUM) denote the approximate trend of cumulate layering. The lines in the residual tectonites (harzburgite) as well as the concordant hachuring in the lower metacumulates represent the trace of the foliation (S_1). Sense of shear is indicated by arrows along the foliation. The lenticular hachured bodies represent the basal dunites (BD). The scale is given in km. (vertical = horizontal).



Ridge Axis
15
10
5
5
10
15
0
5
10
15
PL
PL
IG
IG
IG
IG
C
LG
LG
TZ
TZ
TZ
TZ
EUM
EUM
TRACE OF S_1

as the Trinity ophiolite show different structures, textures and variations in mineralogy and mineral chemistry than the distinctly cumulate dunites at the base of the suite. Quick (in press) studied the dunite bodies exposed in the Trinity Peridotite in California. His chemical and structural analysis led him to propose that these bodies were generated as tracks and trails left behind by upward-migrating basaltic melt. The structures observed within these dunites on Table Mountain could easily be generated by the interaction of a consolidating and subsiding cumulate pile with these "residual" dunites. It is unclear which magma chamber profile would maximize the interface area where the "residual" dunites could accumulate.

Most importantly, the Casey model does not explain the penetrative deformation present in the basal cumulates and residual dunites. These dunites (e.g. from Table Mountain) show very few relict textures and have extremely well-developed olivine fabrics which were generated by plastic flow (Girardeau and Nicolas, 1981). George (1978) argued that strong preferred crystallographic orientation fabrics resulting from plastic flow could only be produced through large amounts of shear strain. The sense of shear recorded in the deformed cumulates on Table Mountain is identical to that indicated by the dunite fabrics as well as that experienced by the upper harzburgites. The similarity in strengths and orientations of the olivine maxima in the "residual" dunites and the upper harzburgites would suggest that these units experienced similar strain histories.

Dewey and Kidd (1977) proposed that the deformation of the basal cumulates is the result of differential subsidence of the young cumulate pile at the bottom of the magma chamber. A mechanical coupling between the uprising melt and hot residual materials (harzburgite and dunite) and the subsiding/consolidating cumulates would explain the inferred similarity in strain histories (Figure VI-4). This coupling would virtually be eliminated with a rapidly tapering, narrow base of the magma chamber. Uprising melt would simply enter the magma chamber while uprising residual materials would interface (hence deform) only the contact between the cumulates and the tectonites.

Subsidence of oceanic crust away from the ridge axis is approximated by the relationship: depth = $2.7 + t^{\frac{1}{2}}/3$ where t is the age in millions of years since formation of the crust. The Bay of Islands Complex was between 20 and 30 ma. at obduction (see Chapter II, p. 20). If approximately 25 million years had elapsed before obduction mechanisms became active, then approximately 1.7 km of subsidence would have occurred. Possibly this may be related to some of the early post-lithification/pre-obduction jointing and minor faulting.

The foliation in the basal cumulates is approximately concordant with that in the residual tectonites distinctly cross cutting the cumulate/residual tectonite contact on Table Mountain. It is likely that the S_1 foliation dips away from the ridge axis because of the herringbone relationship between the foliation and the compositional layering (Girardeau and Nicolas, 1981 and this thesis). Further detailed study of ophiolites with well preserved basal suites as well as a perfection of seismic anisotropy studies will be required to better define the relationship between upper mantle structure and ridge axis orientation or/ridge transform intersection complication.

The basal dunite bodies have often been considered to represent the lowermost cumulate phase. More recent work (Quick, in press; George, 1978) has suggested that these bodies may form by two processes. The uppermost dunites often preserve relict cumulate textures while the fabrics and chemistry of the lowermost bodies indicate that they represent an "ultramafic residuum" left by upwelling picritic melts. Field evidence from Table Mountain supports such a dual origin. The upper dunites grade into layered troctolites and websterites while the lower dunites have a transitional relationship with the uppermost harzburgite.

Yet another structural complexity requiring further detailed examination of residual tectonites are the intermittent reversals in shear sense. Data from Table Mountain suggests that sinistral shearing was dominant in this section and that the reversals reflect complexities along the axial zone of upwelling and underplating beneath a ridge crest.

REFERENCES CITED

Allen, C. R., 1975. The petrology of a portion of the Troodos Plutonic Complex, Cyprus, (Ph.D. thesis): Cambridge University.

Archibald, D. A., and Farrar, E., 1976. K-Ar ages of amphiboles from the Bay of Islands Ophiolite and the Little Port Complex, western Newfoundland, and their geological implications: Can J. Earth Sciences, v. 13, p. 520-529.

Ave Lallement, H. G., 1975. Mechanisms of preferred orientations of olivine in tectonite peridotite: Geology, v. 3, p. 653-656.

Ave Lallement, H. G., and Carter, N. L., 1970. Syntectonic recrystallization of olivine and modes of flow in the upper mantle: Geol. Soc. Amer. Bull., v. 81, p. 2203-2220.

Ave Lallement, H. G., Mercier, J. C., Carter, N. L., and Ross, J. V., 1980. Rheology of the upper mantle: Inferences from peridotite xenoliths: Tectonophysics, v. 70, p. 85-113.

Bailey, E. H., 1981. Pocket map, Geologic map of Muscat-Ibra Area, Sultanate of Oman: Journ. Geophys. Res., v. 86, no. B4.

Bergstrom, S. M., Riva, J., and Kay, M., 1974. Significance of conodonts, graptolites, and shelly faunas from the Ordovician of western Newfoundland: Can. Jour. Earth Sciences, v. 11, p. 1625-1660.

Bezzi, A., and Piccardo, G. B., 1971. Structural features of the Ligurian ophiolites: Petrologic evidence for the "oceanic" floor of the northern Apennines Geosyncline: A contribution to the problem of the Alpine-type Gabbro-Peridotite Associations: Mem. Soc. Geol. It., v. 10, p. 53-63.

Bhattacharji, S., 1967. Scale model experiments on flowage differentiation in sills, in Wyllie, P. J., ed., Ultramafic and Related Rocks: New York, John Wiley and Sons, Inc., p. 69-70.

Bird, J. M. and Dewey, J. F., 1970. Lithosphere plate - Continental margin tectonics and the evolution of the Appalachian Orogen: Geol. Soc. Amer. Bull., v. 81, p. 1031-1060.

Blake, M. C., Jr., and Landis, C. A., 1973. The Dun Mountain ultramafic belt-Permian oceanic crust and upper mantle in New Zealand: U.S.G.S. Jour. Research, v. 1, p. 529-534.

Boer, J. de, and Snider, F. G., 1979. Magnetic and chemical variations of Mesozoic diabase dikes from eastern North America: Evidence for a hot spot in the Carolinas? Geol. Soc. Amer. Bull., v. 90, p. 185-198.

Bonatti, E., and Honnorez, J., 1976. Sections of the earth's crust in the equatorial Atlantic: Jour. Geophys. Res., v. 81, no. 23.

Bonatti, E., Hamlyn, P., and Ottonello, G., 1981. Upper mantle beneath a young oceanic rift: Peridotites from the island of Zabargad (Red Sea): Geology, v. 9, p. 474-479.

Bosworth, W., 1981. Strain induced preferential dissolution of halite: Tectonophysics, v. 78, p. 509-525.

Bottinga, Y., and Steinmetz, L., 1979. A geophysical, geochemical, petrological model of the sub-marine lithosphere: Tectonophysics, v. 55, p. 311-347.

Boudier, F., and Coleman, R. G., 1981. Cross section through the peridotite in the Semail Ophiolite, southeastern Oman: Jour. Geophys. Res., v. 86, no. B4, p. 2573-2592.

Boudier, F. and Nicolos, A., 1972. Fusion partielle gabbroique dans la lherzolite de Lanzo: Schw. Min. und Pet. Mitt., v. 52, p. 39-56.

Boudier, F., and Nicoloas, A., 1977. Structural controls on partial melting in the Lanzo peridotites in H.J.B. Dick ed., Magma Genesis 1977, Proceedings of the A.G.U. Chapman Conference on Partial Melting in the Earth's upper mantle: Bulletin 96, State of Oregon, Department of Geology and Mineral Industries.

Buddington, A. F. and Hess, H. H., 1936. Layered Reid Laccoliths in the Trout River Area, Newfoundland, Amer. Jour. Sci., v. 33, p. 330-388.

Bursnall, J. T., and DeWit, M. J., 1975. Timing and development of the orthotectonic zone in the Appalachian Orogen of Northwest Newfoundland: Can. Jour. Earth Sciences, v. 12, no. 10, p. 1712-1722.

Cann, J. R., 1974. A model for oceanic crustal structure developed: Geophys. Jour. Roy. Astron. Soc., v. 39, p. 169-187.

Carter, N. L., 1976. Steady state flow of rocks: Rev. Geophys. and Space Phys., v. 14, p. 301-360.

Casey, J. F., 1979. Structure within the plutonic section, North Arm Mountain Massif, Bay of Islands Complex: Its bearing on tectonic processes of accreting plate margins: Abstracts of Papers Submitted, International Ophiolite Symposium, Cyprus, Cyprus Geological Survey Department, p. 88-89.

Casey, J. F., 1980. The geology of the southern part of the North Arm Mountain Massif, Bay of Islands Ophiolite Complex, western Newfoundland, with application to ophiolite obduction and the genesis of the plutonic portions of oceanic crust and upper mantle, (Ph.D. thesis): Albany, New York, State University of New York.

Casey, J. F., Dewey, J. F., Fox, P. J., Karson, J. A., and Rosencrantz, E., 1981. Heterogeneous nature of oceanic crust and upper mantle: a perspective from the Bay of Islands ophiolite in The Sea, v. vii, edited by C. Emiliani, John Wiley, New York.

Casey, J. F., and Karson, J. A., 1981. Magma chamber profiles from the Bay of Island Ophiolite Complex: Nature, v. 292, p. 295-301.

Casey, J. F., and Kidd, W. S. F., 1981. A parallochthonous group of sedimentary rocks unconformably overlying the Bay of Islands ophiolite complex, North Arm Mountain, Newfoundland: Can. Jour. Earth Sciences, v. 18, no. 6, p. 1035-1050.

Cassard, B., Rabinovitch, M., Nicolas, A. and Moutte, J., 1980. Structural classification of chromite pods in Southern New Caledonia, Econ. Geol.

Cathles, L. M., III, 1975. The Viscosity of the Earth's Mantle: Princeton, Princeton University Press, 386 p.

Christensen, N. I., and Salisbury, M. H., 1979. Seismic Anisotropy in oceanic upper mantle: evidence from the Bay of Islands Ophiolite complex: Jour. Geophys. Res., v. 84, no. B9, p. 4601-4610.

Church, W. R., 1976. Ages of Zircons from the Bay of Islands ophiolite complex, western Newfoundland: Comment: Geology, v. 4, 623-624.

Church, W. R. and Riccio, L., 1977. Fractionation trends in the Bay of Islands Ophiolite of Newfoundland, polycyclic cumulate sequences in ophiolites and their classification, Canad. Jour. Earth Sci., v. 14, p. 1156-1165.

Church, W. R., and Stevens, R. K., 1971. Early Paleozoic ophiolite complexes of the Newfoundland Appalachians as mantle-oceanic crust sequences: Jour. Geophys. Res., v. 76, no. 5, p. 1460-1466.

Coleman, R. G., 1977. Ophiolites: Ancient oceanic lithosphere, New York, Springer Verlag, 230 p.

Cooper, J. R., 1936. Geology of the Southern half of the Bay of Islands Igneous Complex, Newfoundland Dept. Nat. Res. Geol. Sec. Bull., v. 4, 35 p.

Dallmeyer, R. D., 1977. Diachronous ophiolite obduction in western Newfoundland - Evidence from $^{40}Ar/^{39}Ar$ ages of the Hare Bay metamorphic aureole: Amer. Jour. Sci., v. 277, p. 61-72.

Dallmeyer, R. D., and Williams, H., 1975. $^{40}Ar/^{39}Ar$ ages from the Bay of Islands metamorphic aureole: Their bearing on the timing of Ordovician Ophiolite Obduction: Can. Jour. Earth Sciences, v. 12, p. 1685-1690.

Dalrymple, G. B., 1979. Critical tables for conversion of K-Ar stages from old to new constants: Geology, v. 7, no. 11, p. 558-560.

Darot, M., and Bouchez, J. L., 1976. Study of directional data distributions from principal preferred orientation axes: Jour. Geol., v. 84, p. 239-247.

Darot, M., and Boudier, F., 1975. Mineral lineations in deformed peridotites: Kinematic meaning: Petrologie, v. 1, p. 225-236.

Den Tex, E., 1969. Origin of ultramafic rocks, their tectonic setting and history: a contribution to the discussion of the paper "The origin of ultramafic and ultrabasic rocks" by P. J. Wyllie: Tectonophysics, v. 7.

Dewey, J. F., 1979. Ophiolites: complicated oceanic geology: Abstracts of Papers Submitted, International Ophiolite Symposium, Cyprus, Cyprus Geological Survey Department.

Dewey, J. F., and Bird, J. M., 1971. Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland: Jour. Geophys. Res., v. 76, p. 3179-3206.

Dewey, J. F., and Kidd, W.S.F., 1977. Geometry of plate accretion: Geol. Soc. Amer. Bull., v. 88, p. 960-968.

DeWit, M. J., 1974. On the origin and deformation of the Fleur de Lys metaconglomerate, Appalachian Fold Belt, Northwest Newfoundland: Can. Jour. Earth Sciences, v. 11, p. 1168-1180.

Dick, H.J.B., 1977. Partial melting in the Josephine Peridotite I, The effect on mineral composition and its consequences for geobarometry and geothermometry: Amer. Jour. Sci., v. 277, p. 801-832.

Dick, H.J.B. and Sinton, J. M., 1979. Compositional layering in alpine perdotites: evidence for pressure solution creep in the mantle: Jour. Geol., v. 87, p. 403-416.

Dungan, M. A., and Ave Lallement, H. G., 1977. Formation of small dunite bodies by metasomatic transformation of harzburgite in the Canyon Mountain Ophiolite, northeast Oregon in H.J.B. Dick ed. Magma Genesis 1977, Proceedings of the A.G.U. Chapman Conference on Partial Melting in the Earth's upper mantle: Bulletin 96, State of Oregon, Department of Geology and Mineral Industries.

Durham, W. B., Goetze, C. and Blake, B., 1977. Plastic flow of oriented single crystals of olivine Part II Observations and interpretation of the dislocation structures, Jour. Geophys. Res., v. 82, p. 5755.

England, R. N., and Davies, H. L., 1973. Mineralogy of ultramafic cumulates and tectonites from eastern Papua: Earth Planet. Sci. Letts., v. 17, p. 416-425.

Etchecopar, A., 1974. Simulation par ordinateur de la deformation progressive d'un agregat polycristallin. Etude du developpement de structures orientees par 'ecrasement et cisaillement [these de 3 eme cycle] U. Nantes.

Etchecopar, A. 1981. A plane kinematic model of progressive deformation in a polycrystalline aggregate: Tectonophysics, v. 78.

Fedotov, S. A., 1975. Mechanism of magma ascent and deep feeding channels of Island Arc volcanoes: Bull. Volcan., v. 39, p. 1-241.

Fleet, M. E., 1978. Origin of olivine subgrain boundaries in mantle peridotites: Nature, v. 275, p. 48-50.

Flinn, D., 1962. On folding during three-dimensional progressive deformation: Quart. Jour. Geol. Soc. Lond., v. 118, no. 472, p. 385-433.

Forsyth, D. W., 1977. The evolution of the upper mantle beneath mid-ocean ridges: Tectonophysics, v. 38, p. 89-118.

Fox, P. J., Detrick, R., and Purdy, G., 1979. Evidence for crustal thinning near fracture zones: Implications for ophiolites: Abstracts of Papers Submitted, International Ophiolite Symposium, Cyprus, Cyprus Geological Survey Department.

George, R. P., Jr., 1977. Sub solidus deformation mechanisms and hypersolidus creep of peridotite in H.J.B. Dick ed. Magma Genesis 1977, Proceedings at A.G.U. Chapman conference on Partial Melting in the Earth's upper mantle: Bulletin 96, State of Oregon, Department of Geology and Mineral Industries.

George, R. P., Jr., 1978. Structural petrology of the Olympus ultramafic complex in the Troodes ophiolite, Cyprus: Geol. Soc. Amer. Bull., v. 89, p. 845-865.

Girardeau, J., 1979. Structure des ophiolites de l'ouest de Terre neuve et modele de croute oceanique, (thesis Docterre 3 e cycle): L'Institut des Sciences de la Nature de L' Universite de Nantes.

Girardeau, J., and Nicolas, A., 1981. The structures of two ophiolite massifs Bay of Islands. Newfoundland: A model for the oceanic crust and upper mantle: Tectonophysics, v. 77, p. 1-34.

Green, H. W. and Radcliffe, S. V., 1975. Fluid precipitate in rocks from the earth's mantle. Geol. Soc. Amer. Bull., v. 86, p. 846-852.

Greenbaum, D., 1972. Magmatic processes at ocean ridges, evidence from the Troodos Massifs, Cyprus: Nature, v. 238, p. 18-21.

Hobbs, B. E., Means, W. D., and Williams, P. E., 1976. An Outline of Structural Geology, New York, John Wiley, 571 p.

Hubert, J. F., Suchecki, R. K., Callahan, R.K.M., 1977. The Cow Head Breccia: sedimentology of the Cambro-Ordovician continental margin, Newfoundland. Soc. Econ. Paleont. and Miner. Special Pub. No. 25, p. 125-154.

Ingerson, F. E., 1935. Layered Peridotite Laccoliths of the Trout River Area, Newfoundland, Amer. Jour. Sci., v. 29, p. 422-440.

Jackson, E. D., 1971. Origin of ultramafic rocks by cumulus processes: Fortschr. Mineralogie, v. 48, p. 128-174.

Jackson, E. D., Green, H. W., Moores, E. M., 1975. The Vourinos Ophiolite, Greece: cyclic units of lineated cumulates overlying harzburgite tectonite: Geol. Soc. Amer. Bull., v. 86, p. 390-398.

Jacobson, S. B., and Wasserberg, G. J., 1979. Nd and Sr isotopic study of the Bay of Islands ophiolite complex and the evolution of the source of mid ocean ridge basalts: Jour. of Geophys. Res., v. 84, p. 7429-7445.

Jamieson, R. A., 1979. Ophiolite emplacement as recorded in the dynamothermal aureole of the St. Anthony complex, Northwestern Newfoundland: Abstracts of Papers Submitted, International Ophiolite Symposium, Nicosia, Cyprus, Cyprus Geological Survey, Dept., p. 92.

Jamieson, R. A., 1980. Formation of metamorphic aureoles beneath ophiolites - Evidence from the St. Anthony Complex, Newfoundland: Geology, v. 8, p. 150-154.

Juteau, T., Nicolas, N., Dubessy, J. Fruchard, J. C., and Bouchez, J. L., 1977. Structural relationships in the Antalya ophiolite complex, Turkey: Possible model for an oceanic ridge: Geol. Soc. Amer. Bull., v. 88, p. 1740-1748.

Karson, J. A., 1977. Geology of the northern Lewis Hills, Western Newfoundland. (Ph.D. thesis): Albany, New York, State University of New York.

Karson, J. A., and Dewey, J. F., 1978. Coastal Complex, western Newfoundland: An Early Ordovician oceanic fracture zone. Geol. Soc. Amer. Bull., v. 89, p. 1037-1049.

Kidd, R.G.W., Cann, J. R. 1974. Chilling statistics indicate an ocean floor spreading origin for the Troodos Complex, Cyprus. Earth Planet. Sci. Lett., v. 24, p. 151-155.

Kidd, W.S.F., 1974. Evolution of the Baie Verte Lineament, Burlington Peninsula, Newfoundland. Unpub. Ph.D. dissertation University of Cambridge.

Kindle, C. H. and Whittington, H. B., 1958. Stratigraphy of the Cow Head region, western Newfoundland, Geol. Soc. Amer. Bull., v. 69, p. 315-342.

Kirby, St. H. 1977. State of stress in the lithosphere: Inferences from steady-state flow of rocks: Pageophys., v. 115.

Klappa, C. F., Opalinsky, P. R. & James, N. P., 1980. Middle Ordovician Table Head Group of western Newfoundland: a revised stratigraphy, Can. Jour. of Earth Sci., v. 17, no. 8, p. 1007-1019.

Lindsley-Griffin, N., 1977. The Trinity Ophiolite, Klamath Mountains, California; in, Coleman, R. G. and Irwin, W. P., Eds., North American Ophiolites, State of Oregon Dept. of Geology and Mineral Resources Bull., v. 95, p. 107-120.

Lister, C.R.B., 1977. Qualitative Models of Spreading Center Processes, Including Hydrothermal Penetration: Tectonophysics, v. 37, p. 203-218.

Loney, R.A., Himmelberg, G.R. & Coleman, R. G., 1971. Structure and petrology of the Alpine-type Peridotite at Burro Mountain, California, U.S.A., Jour. of Petrology, v. 12, part 2, 245-309.

Loney, R.A. and Himmelberg, G. R., 1977. Geology of the gabbroic complex along the northern border of the Josephine Peridotite, Vulcan Peak area, Southwestern Oregon. Jour. Research U.S. Geol. Survey, v. 5, no. 6, p. 761-781.

Malpas, J., The "petrological moho" as identified in the Bay of Islands Igneous complex. Western Newfoundland, unpublished manuscript.

Malpas, J., 1977. Petrology and tectonic significance of Newfoundland ophiolites with examples from the Bay of Islands. In North American Ophiolites, Edited by R. G. Coleman and W. P. Irwin. Oregon Department of Geology and Mineral Industries, Bulletin 95, pp. 12-23.

Malpas, J., 1979. The dynamothermal aureole of the Bay of Islands ophiolite suite. Canadian Journal of Earth Sciences, 16, pp. 2086-2101.

Mattison, J. M., 1975. Early Paleozoic ophiolite complexes of Newfoundland: Isotopic ages of zircons: Geology, v. 3, p. 181-183.

Mattison, J. M., 1976. Ages of Zircons from the Bay of Islands ophiolite complex, western Newfoundland: Geology, v. 4, p. 393-394.

Means, W. D., 1981. The concept of steady-state foliation. Tectonophysics, v. 78, p. 179-199.

Means, W. D., and Xia, Z. G., 1981. Deformation of crystalline materials in thin section: Geology, v. 9, p. 538-543.

Melosh, J., 1977. Shear stress on the base of a lithospheric plate: Pageophy, v. 115, p. 429.

Menzies, M., 1977. Residual alpine lherzolites and harzburgites - geochemical and isotopic constraints on their origin, in Magma Genesis 1977, Am. Geophys. Un. Chapman conference on Partial Melting in the Earth's Upper Mantle, State of Oregon Dept. of Geology and Mineral Industries, v. 96, p. 129-147.

Menzies, M. and Allen, C. 1974. Plagioclase lherzolite - residual mantle relationships within two eastern Mediterranean ophiolites Contr. Min. & Petrology, v. 45, p. 197-213.

Mercier, J. C., 1976. Single pyroxene geothermometry and geobarometry: Amer. Min., v. 61, p. 603-615.

Mercier, J. C., 1977. Natural Peridotites: Heterogeneity of the Upper Mantle. Ph. D. Thesis, State University of New York, Stony Brook, 688 p.

Mercier, J. C., Anderson, D. A. and Carter, N. L., 1977. Stress in the lithosphere: inferences from steady state flow of rocks: Pure Appl. Geophys., v. 115.

Mercier, J. C. and Nicolas, A., 1975. Textures and fabrics of upper mantle peridotites as illustrated by xenoliths from basalts: Jour. Petrology, v. 16, no. 2, p. 454-487.

Moore, J. G., Fleming, H. S., Phillips, J. D., 1974. Preliminary model for extrusion and rifting of the axis of MAR 36° 48' N: Geology, v. 2, p. 437-440.

Moores, E. M., 1969. Petrology and structures of the Vourinos Ophiolite Complex, northern Greece, Geol. Soc. Amer. Spec. Paper 118, 73 p.

Moores, E. M., and Jackson, E. D., 1974. Ophiolites and oceanic crust: Nature, v. 250, p. 136-139.

Moores, E. M. and Vine, F. J., 1971. The Troodos Massif, Cyprus and other ophiolites and oceanic crust: evaluation and implications, Phil. Trans. R. Soc. London, v. A 268, 443-466.

Nelson, K. D. and Rosencrantz, E., in press. Floating Lids on Mid-Ocean Spreading Center Magma Chambers.

Nicolas, A., 1976. Flow in upper mantle rocks: Some geophysical and geodynamical consequences, Tectonophys., v. 32, p. 93-106.

Nicolas, A. and Boudier, F., 1975. Kinematic interpretation of folds in Alpine-type peridotites: Tectonophysics, v. 25, p. 233-260.

Nicolas, A., Bouchez, J. L., Boudier, F., and Mercier, J. C., 1971. Textures, structures and fabrics due to solid state flow in some European lherzolites: Tectonophysics, v. 12, p. 55-86.

Nicolas, A., Boudier, F., Bouchez, J. L., 1979. Interpretation of peridotite structures from ophiolitic and oceanic environments: preprint of unpublished paper given at the International Ophiolite Symposium Nicosia, Cyprus.

Nicolas, A., Boudier, F., and Boullier, A. M., 1973. Mechamisms of flow in naturally and experimentally deformed peridotites. Amer. Jour. Sci., v. 273, p. 853-876.

Nicolas, A. and Jackson, E. D., 1972. Repartition en deux provinces des peridotites des chaines alpines logeant la Mediterranee: implications geotectonique: Schw. Min. und Pet. Mitt., v. 52, p. 479-495.

Nicolas, A. and Poirier, J. P., 1976. Crystalline plasticity and solid state flow in metamorphic rocks. New York, Wiley Interscience, 392 p.

O'Connell, S., 1979. Geology of the mafic/ultramafic transition, Table Mountain, West Newfoundland. M. Sci. Thesis, State University of New York, Albany.

Pallister, J. S. and Hopson, C. A., 1981. Semail Ophiolite Plutonic suite: Field relations, phase variations, cryptic variation and layering and a model of a spreading ridge magma chamber: Jour. Geophys. Res., v. 86, no. B4, p. 2593-2644.

Poirier, J. P. and Nicolas, A., 1975. Deformation - induced recrystallization by progressive misorientation of subgrain - boundaries, with special references to mantle peridotites: Jour. Geology, v. 83, p. 707-720.

Pringle, R., Miller, J. A. and Warrell, D. M., 1971. Radiometric age determinations, from the Long Range Mountains, Newfoundland Can. Jour. Earth Sci., v. 8, 1325-1330.

Quick, James E., in press. The origin and significance of large, tabular dunite bodies in the Trinity Peridotite, Northern California. (Submitted to Contrib. to Min. and Petrol. Apr. '81).

Quick, James E., in press. Petrology and petrogenesis of the Trinity Peridotite, an upper mantle diapir in the eastern Klamath Mountains, northern California. (Submitted to Jour. of Geophys. Res. Nov. 1980).

Raleigh, C. B., 1968. Mechanisms of plastic deformation of olivine: Jour. Geophys. Res., v. 73, p. 5391-5406.

Raleigh, C. B. and Kirby, S. H., 1970. Creep in the upper mantle: Min. Soc. Am., Spec. Paper 3, p. 113-121.

Ramsay, J. G., 1967. Folding and Fracturing of Rocks: New York, McGraw-Hill, 568 p.

Ramsay, J. G. and Graham, R. H., 1970. Strain variation in shear belts, Canad. Jour. E. Sci., v. 7, p. 786.

Roeder, D., Mull, C. G., 1978. Tectonics of Brooks Range Ophiolites, Alaska, A.A.P.G. Bull., v. 62, no. 9, p. 1696-1713.

Rosencrantz, E. J., 1980. The geology of the northern part of North Arm Massif, Bay of Islands Ophiolite Complex, Newfoundland: With application to upper oceanic crust lithology, structure, and genesis. Ph.D. thesis, State University of New York, Albany.

Rosendahl, B. R., Raitt, R. W., Dorman, L. M., Bibee, R., Hussong, D. M. and Sutton, G. H., 1976. Evolution of oceanic crust: A physical model of the East Pacific Rise crest derived from seismic refraction data: J. Geophys. Res., v. 81, p. 5294-5304.

Ross, J. V., 1977. The internal fabric of an alpine peridotite near Pinchi Lake, central British Columbia, Canad. Jour. Earth. Sci. v. 14, p. 32-44.

Ross, J. V. and Ave Lallemant, H. G., 1979. Activation Volume for Creep in the Upper Mantle: Science, v. 203.

Ross, J. V., Mercier, J. C., Ave Lallemant, H. G., Carter, N. L. and Zimmerman, J., 1980. The Vourinos Ophiolite Complex, Greece: The tectonite suite: Tectonophysics, v. 70, p. 63-83.

Simonian, K. O. and Gass, I. G., 1978. Arakapas fault belt, Cyprus: A fossil transform fault: Geol. Soc. Amer. Bull., v. 89, p. 1220-1230.

Sleep, N. H., 1975. Formation of oceanic crust: some thermal constraints: Jour. Geophys. Res., v. 80, p. 4033-4042.

Smewing, J. D., Simonian, K. O., and Gass, I. G., 1975. Metabasalts from the Troodos Massif, Cyprus: Genetic implication deduced from petrographic and trace geochemistry: Cont. Min. Pet., v. 51, p. 49-64.

Smith, C. H., 1951. Geological Map of Bay of Islands. Dept. of Mines and Technical Surveys.

Smith, C. H., 1958. Bay of Islands igneous complex, western Newfoundland. Geological Survey of Canada, Memoir 290, 132 p.

Snelgrove, A. K., 1934. Chromite deposits of Newfoundland. Newfoundland Dept. of Nat. Res. Geol. Sec. Bull., no. 1.

Steiger, R. H. and Jager, E., 1978. Subcommission on geochronology: conventions on the use of decay constants in geochronology and cosmochronology in Cohee et al Contr. to Geologic Time Scale, AAPG Studies in Geology, no. 6, p. 67-71.

Stevens, R. K., 1970. Cambro-Ordovician flysch sedimentation and tectonics in west Newfoundland and their possible bearing on a proto-Atlantic Ocean. Geol. Assoc. of Canada, Spec. Paper, v. 7, p. 169-177.

Stevens, R. K., 1976. Lower Paleozoic evolution of western Newfoundland. Unpub. Ph.D. Thesis, Memorial Univ. of Newfoundland.

Strong, D. F. and Williams, H., 1972. Early Paleozoic flood basalts of Northwest Newfoundland: their petrography and tectonic significance. Geol. Assoc. Can. Proc., v. 24, No. 2, p. 43-54.

Stukas, V. and Reynolds, P. H., 1974. $^{40}Ar/^{39}Ar$ dating of the Long Range dikes, Newfoundland. Earth Planet. Sci. Letts., v. 22, p. 256-266.

Sullivan, J. W., 1981. Some Chemical and Mineralogical Aspects of Plutonic Rocks from the North Arm Mountain Massif, Bay of Islands Ophiolite, Newfoundland. M. Sc. Thesis, State University of New York of Albany.

Turner, F. J. and Weiss, L. E., 1963. Structural Analysis of Metamorphic Tectonites: McGraw-Hill, New York, p. 545.

Twiss, R. J., 1976. Structural super-plastic creep and linear viscosity in the earth's mantle. Earth. Planet. Sci. Letts. v. 33, p. 86-100.

Veevers, J. J., 1977. Paleobathymetry of the crest of spreading ridges related to the age of ocean basins. Earth Planet. Sci. Letts., v. 34, p. 100-106.

Wager, L. R., Brown, G. M. and Wadsworth, W. J., 1960. Types of Igneous Cumulates: Jour. Petrol., v. 1, part 1, p. 73-85.

Whittington, H. B. and Kindle, C. H., 1969. Middle Ordovician Table Head Formation, western Newfoundland. Geol. Soc. Amer. Bull. v. 74, p. 745-758.

Williams, H., 1971. Mafic-ultramafic complexes in western Newfoundland and the evidence for their transportation: a review and interim report. Geological Association of Canada Proceedings, A Newfoundland Decade 24, pp. 9-25.

Williams, H., 1972. Bay of Islands Map Area (12 q), Newfoundland Final map with descriptive notes. Geol. Soc. Canada.

Williams, H., 1973. Bay of Islands map-area, Newfoundland. Geological Survey of Canada, Paper 72-34 and map.

Williams, H., 1975. Structural succession, nomenclature and interpretation of transported rocks in western Newfoundland.

Williams, H., 1977. Ophiolitic melange and its significance in the Fleur de Lys Supergroup, northern Appalachians, Can. Jour. Earth Sci., v. 14, p. 987-1003.

Williams, H., 1979. Appalachian Orogen in Canada. Canadian Journal of Earth Sciences, 16, pp. 792-807.

Williams, H. and Godfrey, S. C., 1980. Carbonate Slivers Within the Humber Arm Allochthon, Newfoundland. Geol. Soc. Amer. Abstracts with programs, v. 12, no. 2, p. 89.

Williams, H., Hibbard, J. P., Bursnall, J. T., 1977. Geologic setting of asbestos-bearing ultramafic rocks along the Baie Verte Linenment, Newfoundland. Geol. Surv. Can. Paper 77-1, pt. A, 351-360.

Williams, H. and Malpas, J., 1972. Sheeted dikes and brecciated dike rocks within transported igneous complexes. Bay of Islands, western Newfoundland, Canad. Jour. Earth. Sci., v. 9, p. 1216.

Williams, H. and Smyth, W. R., 1973. Metamorphic aureoles beneath ophiolite suites and alpine peridotites: tectonic implications with west Newfoundland examples, Amer. Jour. Sci., v. 273, p. 594-621.

Williams, H. and Stevens, R. K., 1969. Geology of Belle Isle: northern extremity of the deformed Appalachian mid geosynclinal belt, Can. Jour. Earth Sci., v. 6, no. 5, p. 1145-1157.