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# METAMORPHIC AUREOLES BENEATH OPHIOLITE SUITES AND ALPINE PERIDOTITES: TECTONIC IMPLICATIONS WITH WEST NEWFOUNDLAND EXAMPLES

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ABSTRACT. Metamorphic aureoles that are attached to the stratigraphic base of transported ophiolite sequences or sheet-like bodies of Alpine peridotite do not have a satisfactory explanation, and they have been largely neglected in recent plate tectonic models of obduction and transport of oceanic crust and mantle. The Bay of Islands Complex and the White Hills Peridotite Sheet in western Newfoundland display identical basal aureoles that consist of pyroxene-bearing amphibolites, amphibolites, and greenschists, with metamorphic grade and polyphase deformation decreasing structurally downward and away from the overlying ultramafic rocks. Textural evidence, gradational relationships, and structural and stratigraphic syntheses indicate that the aureoles were stamped upon essentially undeformed and unmetamorphosed supracrustal rocks that lay at or near a continental margin.

The metamorphic rocks are viewed as contact dynamo-thermal aureoles related to obduction and early transport of oceanic crust and mantle. Following the formation of the aureoles, they moved as integral parts of the ophiolite slices for at least 80 to 105 km, mainly by gravity sliding. Aureoles beneath ophiolite sequences and Alpine peridotites in other parts of the world are thought to bear certain similarities to the well-exposed west Newfoundland examples.

## INTRODUCTION

Metamorphic aureoles that underlie Alpine peridotites at the base of ophiolite suites or that partially surround isolated bodies of Alpine peridotite are common in many parts of the world (Challis, 1965; Dickey, 1970; Green, 1964; Karamata, 1968; Loomis, 1972; MacGregor, 1964; MacKenzie, 1960; Smith, 1958). The absence of aureole rocks in many other examples can be considered as the result of structural omission rather than a primary absence, for most ophiolite suites and Alpine peridotites are fault-bounded. In all cases, the interpretation of the metamorphic rocks, that is, their heat source, structures, age, and provenance, is critical to the interpretation of the history of the plutonic rocks.

Earlier views on the petrogenesis and mode of emplacement of Alpine peridotites were largely conditioned by the presence of metamorphic aureoles that are clearly related to the ultramafic plutons. The usual interpretation that metamorphic aureoles are the result of intrusion of hot magma and conduction of heat outward from the contacts naturally led in some cases to the view that Alpine peridotites are hot intrusions with the ultramafic fraction originating in the crust as an ultramafic cumulate, for example, McTaggart (1971).

In most recent interpretations, ophiolite suites are viewed as transported oceanic crust and mantle (Bailey, Blake, and Jones, 1970; Church, 1972; Coleman, 1971; Davies and Smith, 1971; Dewey and Bird, 1971; Moores, 1970; Reinhardt, 1969; Stevens, 1970; Upadhyay, Dewey, and Neale, 1971; Williams and Malpas, 1972). This model is now considered as virtually assured in many geological circles, yet few analyses of ophiolite sequences attempt to reconcile the aureole rocks and to explore their implications in the context of plate tectonic models. The analogy between the ophiolite suite and oceanic crust and mantle is particularly forceful and is based upon the following considerations:

1. Similarities in the gross physical characteristics of the ophiolite suite with geophysical models of oceanic crust and mantle (Le Pichon, 1969).
2. Transported on-land ophiolite is rooted in oceanic lithosphere at Papua, New Guinea (Davies and Smith, 1971).
3. Strong lithologic similarities between the ophiolite suite and rocks of Macquarie Ridge (including sheeted dikes) where exposed and mapped at Macquarie Island (Varne and Rubenach, 1972).
4. Lithological and chemical similarities of oceanic tholeiites and pillow lavas of ophiolite suites (for example, Aumento, Loncarevic, and Ross, 1971).
5. A model involving sea floor spreading as the only reasonable explanation for the extensive development of sheeted dikes like those in ophiolite complexes.
6. High pressure mineralogy of certain Alpine peridotites requiring mantle depths for conditions of crystallization (for example, Church, 1972).
7. Preponderance of metamorphic tectonites in the ultramafic fraction of ophiolites that display textures like those experimentally reproduced at conditions representative of the mantle (Nicolas, 1969; Nicolas, Boucheg, and Brudier, 1972; Ave'Lallemant and Carter, 1970).
8. Similar metamorphic mineral assemblages in oceanic rocks at mid-ocean ridges compared with those in ophiolites and similar vertical metamorphic variations related to geothermal gradient and depth of burial (Williams and Malpas, 1972).

Most large isolated bodies of Alpine peridotite are lithologically and texturally similar to ultramafic rocks of the ophiolite suite. Their interpretation has therefore gained considerable new significance, for like the ultramafic rocks of ophiolite suites, they are of comparable size, they occur in the same geologic settings, and many display the same high pressure mineral phases, for example, Medaris (1972). Accordingly, isolated Alpine peridotites that resemble ultramafic rocks of ophiolite suites are now interpreted as either the dismembered ultramafic fractions or eroded remnants of once-more-continuous ophiolite sequences, or else they are interpreted as mantle diapirs, for example, Loomis (1972). Of course not all ultramafic rocks in orogenic belts can be interpreted in this way. Some, previously classed as Alpine peridotites (Hess, 1955) are intrusive sills or plugs of obviously different significance, and others are nondescript serpentinites of unknown affinity. We prefer to restrict the term Alpine peridotite to those ultramafic bodies in orogenic belts that are of mantle derivation (see also Thayer, 1960; Jackson and Thayer, 1972). Of these, the transported ophiolites would appear to provide the largest and commonest examples.

Recent discussions by McTaggart (1972) and Moores and Raymond (1972) clearly contrast the earlier and more recent views on the origin of Alpine peridotites that obviously need reconciliation. On the one hand, the Alpine peridotites are interpreted as orthodox crustal intrusions as evidenced, in part, by their surrounding aureoles (McTaggart, 1972), and on the other hand, they are interpreted as mantle and dismembered parts of ophiolite suites based, in large part, on the analogy between the ophiolite suite and oceanic crust and mantle (Moores and Raymond, 1972). The first interpretation negates the second, and the second makes no attempt to re-interpret the field evidence on which the first is based.

This general failure to account for the metamorphic aureole rocks in recent plate tectonic models has the overall effect of subtracting from the otherwise clear analogy and attractive interpretation of ophiolitic suites as on-land portions of oceanic crust and mantle. If Alpine peridotites are mantle-derived and are in most cases simply the ultramafic fraction of ophiolite suites (now largely dismembered), then their surrounding metamorphic rocks cannot represent conventional thermal aureoles. Rather they must have some special significance that relates to obduction or later tectonism and metamorphism.

*Purpose and scope.*—The characteristics that have led to the opposing interpretations of the Alpine plutonic rocks, either as orthodox intrusions or as obducted oceanic crust and mantle, are superbly combined in the Bay of Islands Complex and the White Hills Peridotite Sheet of western Newfoundland. The Bay of Islands Complex has a clear geologic setting, sharp internal relationships, structural simplicity, a well-exposed complete sequence of ophiolite units, and a well-developed and attached metamorphic aureole exposed beneath its ultramafic rocks. The White Hills Peridotite Sheet, in a similar tectonic setting, also has a well-developed basal aureole that is especially easy of access because of its subhorizontal attitude and therefore wide exposure over gently-rolling terrane. The Newfoundland examples therefore offer an excellent opportunity to study the aureole rocks in a locality where they are clearly attached to a complete ophiolite suite and where their interpretation as strictly thermal aureoles around crustal intrusions is especially enigmatic.

The purpose of this paper is therefore to describe the distribution and special setting of the metamorphic aureole rocks in western Newfoundland and to comment upon their lithologic, petrologic, metamorphic, and structural features as they relate to ophiolite obduction and subsequent transport. Hopefully, this model will have other application in places where the form and structural setting of the aureole rocks are less well known. Most of the information is based upon the authors' studies of ophiolites in western Newfoundland over the past three field seasons. More detailed studies of chemistry and metamorphism of the aureole rocks are presently in progress, notably by J. G. Malpas as part of his Ph.D. studies, and by others at Memorial University.

## REGIONAL SETTING OF WESTERN NEWFOUNDLAND OPHIOLITES

The geology of western Newfoundland is typical of that along the western side of the Appalachian system, and the main tectonic elements are summarized in figure 1. The Precambrian crystalline basement is unconformably overlain by a Cambrian-Ordovician mainly carbonate sequence that is structurally overlain by several transported rock assemblages, all essentially coeval and comprising a number of separate and distinct sub-horizontal slices that were emplaced during the Middle Ordovician. Lower structural slices consist of Cambrian and Lower Ordovician chiefly clastic sedimentary rocks. These are overlain by higher structural slices that consist mainly of contrasting igneous assemblages. In both the Bay of Islands and Hare Bay areas, the highest structural slice is comprised of the ophiolite assemblage and its basal greenschist–

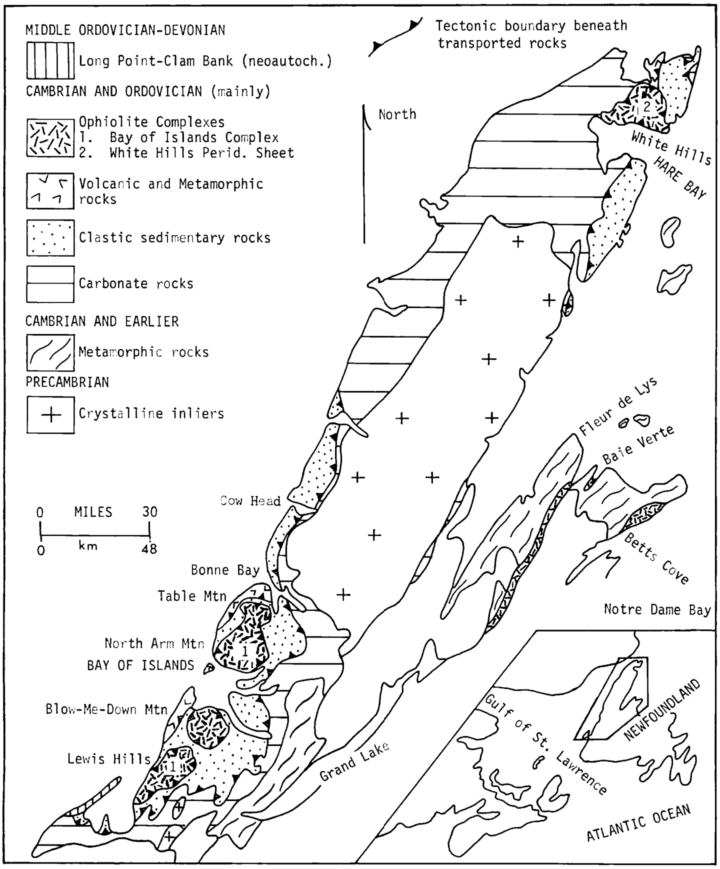

Fig. 1. Major tectonic elements of western Newfoundland.

amphibolite metamorphic aureole. Both the Bay of Islands and White Hills ophiolites are of Early Ordovician age or slightly older, so that they were transported and emplaced soon after their formation. Since emplacement in western Newfoundland, the plutons lay essentially outside the effective realm of Mid-Paleozoic orogenesis that was so widespread and intense in central Newfoundland.

In the Bay of Islands area the ophiolite units are referred to collectively as the Bay of Islands Complex (Cooper, 1936; Smith, 1958), which is represented in four separate massifs, namely, Lewis Hills, Blow-Me-Down Mountain, North Arm Mountain, and Table Mountain (fig. 3), all in the same structural position and either representing separate transported bodies or erosional remnants of a once-continuous slice (Williams, 1971). Two of the massifs (Blow-Me-Down Mountain and North Arm Mountain) display a completely developed ophiolite suite, but all four include the basal peridotite unit, which in each case overlies a metamorphic aureole.

In the Hare Bay area (fig. 2) only the ultramafic part of the ophiolite suite is present in the highest structural slice. There, the ultramafic rocks are referred to as the White Hills Peridotite Sheet (Cooper, 1937). As in the case of the Bay of Islands Complex, the peridotites overlie a metamorphic aureole that forms an integral part of the highest structural slice. Nearby, similar metamorphic rocks without overlying peridotites occur in the same structural position and show reverse metamorphic zonation, and they are thought to represent erosional outliers of the basal portion of the structural slice that includes the White Hills Peridotite Sheet. The greenschists of the metamorphic aureole in this area have been referred to as the Goose Cove Schist (Cooper, 1937) or the Goose Cove Formation (Williams, Smyth, and Stevens, 1973). Tuke (1968) and Smyth (1971) referred all the metamorphic aureole rocks in this area (including amphibolites and pyroxene-bearing amphibolites) to the Goose Cove Formation. Rocks of the metamorphic aureole in the Bay of Islands area are unnamed.

The separation of all the transported rocks into distinct assemblages and the determination of their order of structural stacking have recently been completed for both the Bay of Islands and Hare Bay areas (Williams, Malpas, and Comeau, 1972; Williams, Smyth, and Stevens, 1973; Williams, 1973). No systematic age patterns among the transported rocks are evident in the structural sacking order, for example, such as higher structural slices containing the stratigraphically oldest rocks, but structural analysis and facies restoration indicate that the structurally highest slices are the farthest travelled. The stratigraphic and structural evolution of western Newfoundland is interpreted to relate to the development of a continental margin that reached a climax by the obduction of oceanic crust and mantle westward upon the continent (Stevens, 1970; Williams, 1971; Williams, Malpas, and Comeau, 1972; William, Smyth, and Stevens, 1973).

The transported slices are underlain in most places by a shaly mélange with sedimentary, volcanic, and plutonic exotic blocks. These mélanges probably formed during the later stages of transport when the slices moved across a shaly sedimentary terrane by gravity sliding. The local occurrence of greenschist blocks in some mélanges and large serpentinite, gabbro, diorite, and volcanic blocks within even the lower mélanges that separate sedimentary rock slices clearly attest to the proximity of the higher igneous slices during formation of the mélanges. This implies that the lowermost tectonic mélange contacts are the surfaces of latest move-

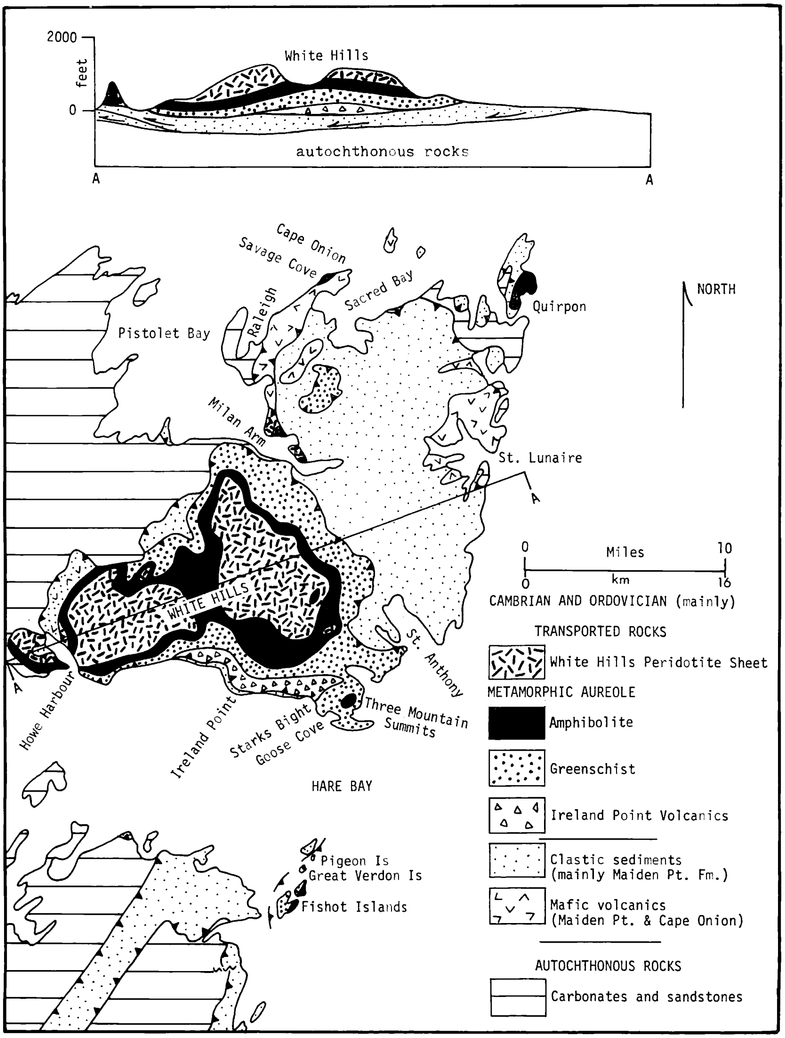

Fig. 2. The geologic setting of the White Hills Peridotite Sheet and the location, extent, and zonation of its metamorphic aureole.

ment and that the transported rocks were emplaced along them as an already assembled allochthon (Stevens and Williams, 1973). The ophiolite suite is interpreted as the first slice to move, and this is further supported by ophiolite detritus in Lower Ordovician sediments that form parts of underlying transported slices (Stevens, 1970).

Penetrative fabrics within the aureole rocks of the highest structural slices are absent in sedimentary rocks of lower structural slices and in underlying autochthonous rocks. This relationship indicates that these aureole rocks were involved in the earliest and most intense deformations that occurred farthest east and predated later gravity sliding. This conclusion is also supported by the local occurrence of schistose inclusions of aureole rocks in much less deformed and metamorphosed mélange such as occurs beneath the highest transported slice on the north side of Hare Bay.

The metamorphic aureole rocks form a concordant zone of less than 300 m in structural thickness at the stratigraphic base of the ophiolite complexes. The contact between the aureole and overlying ultramafic rocks is interpreted as the level of earliest transport or displacement of the ophiolites, and it is to be distinguished from the present structural base of any complex that represents the contact of latest transport or emplacement. Where the stratigraphic base of the complexes is subhorizontal, the aureole parallels the present subhorizontal tectonic base of the structural slice (for example, White Hills Peridotite Sheet, fig. 2). Elsewhere, moderately-dipping sequences of ophiolite rock units and underlying aureoles are truncated by the present subhorizontal tectonic bases of the structural slices (for example, Bay of Islands Complex, fig. 3). The metamorphic rocks exhibit decreasing metamorphic grade and decreasing intensity of deformation downward from the stratigraphic base of the ultramafic rocks. The rock types represented, from structurally highest to structurally lowest, are as follows: banded pyroxene-bearing amphibolite, garnetiferous amphibolite, black amphibolite, chlorite-actinolite schist, greenschist, garnetiferous phyllite, and relatively unmetamorphosed sedimentary and volcanic rocks. The amphibolites and greenschists form the most easily mappable zones, about 100 to 150 m in structural thickness, especially in the case of the White Hills Peridotite Sheet where the aureole is subhorizontal and consequently areally extensive.

## PREVIOUS INTERPRETATIONS OF THE WEST NEWFOUNDLAND AUREOLE ROCKS

Prior to 1970 when the west Newfoundland ophiolites were first viewed as oceanic crust and mantle (Stevens, 1970; Church and Stevens, 1970a), the metamorphic aureole rocks were interpreted as the result of intrusion of mafic magma into the upper crust. Smith (1958) and all previous workers regarded the Bay of Islands Complex and surrounding rocks as essentially autochthonous. This view required that the aureole resulted from contact metamorphism around a hot intrusion, with accompanying metasomatism to account for the chemical differences between the amphibolites at the contacts and regionally surrounding arenaceous sediments from which the amphibolites were thought to have been derived in the case of the Bay of Islands Complex (Smith, 1958, p 19).

Cooper (1937) clearly recognized the White Hills Peridotite Sheet and its aureole as integral parts of a subhorizontal thrust slice. He viewed the amphibolites and greenschists as an aureole that was derived mainly from mafic volcanic rocks by the intrusion of peridotites. The complex structural style of the aureole compared to nearby rocks was attributed to

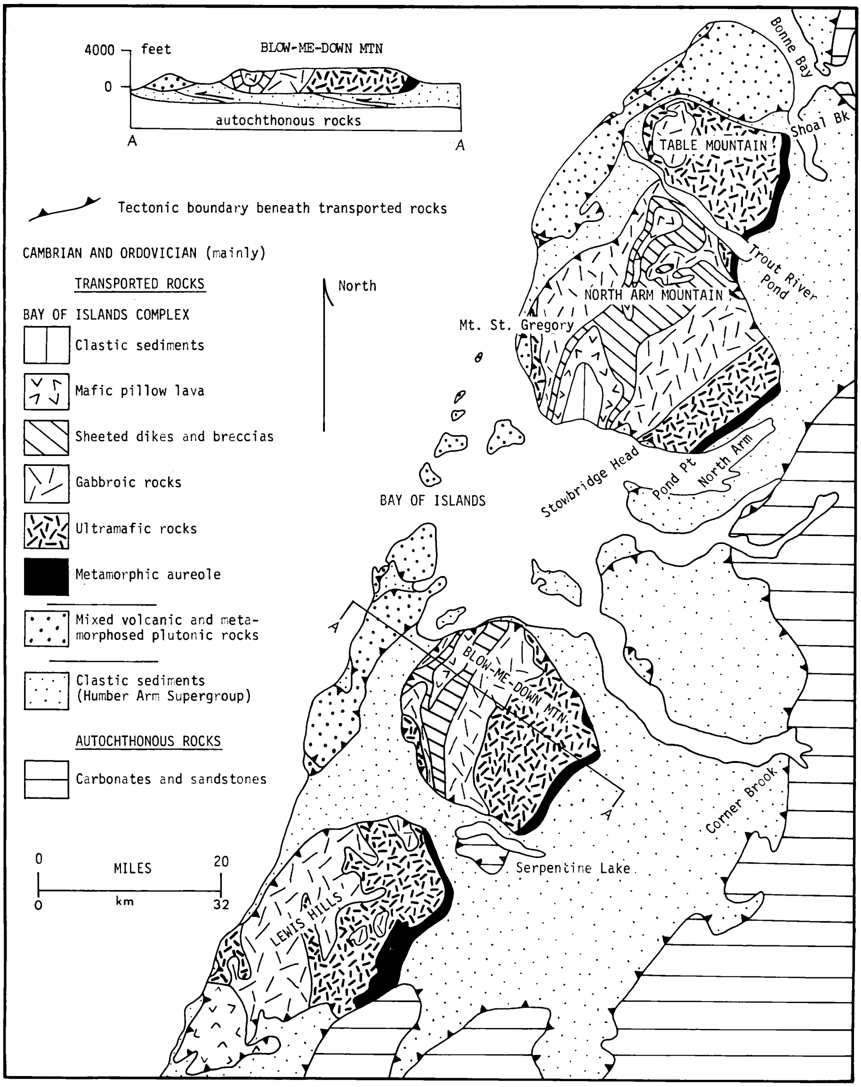

Fig. 3. The geologic setting of the Bay of Islands Complex and the location and extent of its metamorphic aureole.

its proximity to the underlying thrust along which the metamorphic rocks and their overlying peridotites were transported (Cooper, 1937, p. 17).

Tuke (1968) considered the aureole of the White Hills Peridotite Sheet to have been derived from volcanic rocks "most of which have been metamorphosed to amphibolite by the emplacement of the overlying ultrabasic mass" (Tuke, 1968, p. 507). At about the same time, Stevens (1968, p. 8) regarded the aureole of the White Hills Peridotite Sheet as "a basal greenschist unit showing polyphase deformation and low grade metamorphism, overprinted by thermal metamorphism bordering ultramafic intrusions".

Stevens (1970), Church and Stevens (1970a, 1970b, 1971), and Church (1972) interpreted the Bay of Islands Complex and White Hills Peridotite Sheet as transported oceanic crust and mantle. According to this model, they favored a hypothesis involving the emplacement of the ophiolite complexes as hot solids with enough inherent heat to accomplish contact metamorphism. However, they also suggested that frictional heat produced by movement of a cold solid mass might also suffice. In either case, the aureole was thought to include only the amphibolites, at most, or else only the thin pyroxene-bearing zone "superposed on mafic schists with a preexisting regional metamorphic fabric" (Church, 1972, p. 74). They therefore viewed the aureole as a narrow zone of contact heating that was superposed upon already regionally deformed and metamorphosed rocks. This interpretation further implies that the emplacement of the ophiolites was post-tectonic with respect to structures within the underlying rocks of the same slices.

Smyth (1971) showed that the greenschists and amphibolites on the south side of Hare Bay have the same complex structural histories and that the growth of metamorphic minerals in the amphibolites accompanied the first and second deformations. He therefore concluded that if the heat was supplied by the nearby overlying ultramafic plutons, then the ultramafic rocks must have been emplaced before or during the first and second deformations. This implies that all the structure and metamorphism in the rocks beneath the ultramafic plutons is related to their emplacement and that these effects were stamped upon essentially undeformed rocks.

Malpas, Stevens, and Strong (1973) classified the amphibolites of the west Newfoundland aureoles as "amphibolite associated with ophiolite obduction" in an attempt to classify all amphibolites that occur in regional association with ophiolites.

## THE METAMORPHIC AUREOLE OF THE WHITE HILLS PERIDOTITE SHEET

*Distribution.*—The aureole of the White Hills Peridotite Sheet structurally underlies and, in map-view, concentrically surrounds the two main occurrences of ultramafic rocks that form tabular bodies, each 6 km across, in the White Hills north of Hare Bay. The aureole varies in outcrop width from less than a kilometer to 6 km or more, depending upon its attitude, although it is thought nowhere to exceed 300 m in structural thickness.

A smaller body of peridotite with aureole rock nearby along its southern side occurs west of Howe Harbour, and several smaller occurrences of peridotite and amphibolite in irregular dispositions are known at Milan Arm (fig. 2).

In the White Hills, the peridotites form the highest ground, and they are followed outward and at lower elevations by a continuous zone of amphibolite from 1 km to 3 km in outcrop width, in turn followed by a wider zone of greenschists. This outcrop pattern and the present topography are a direct result of the subhorizontal attitude of the ultramafic rocks and underlying aureole rocks within the same subhorizontal structural slice. Locally, ultramafic outliers occur within the amphibolites, and in one locality a topographic depression within the White Hills Peridotite Sheet is bottomed by amphibolite; all confirming a subhorizontal attitude of the rock units.

The tectonic contact at the base of the structural slice that contains the White Hills Peridotite Sheet and its aureole is in most places marked by a shaly mélange. This mélange either overlies allochthonous rocks (Maiden Point or Northwest Arm Formations) or else lies directly upon autochthonous rocks of the Goose Tickle Formation (Williams, Smyth, and Stevens, 1973). In most places the present tectonic base follows the greenschist horizon of the aureole, but locally it cuts downward to relatively unmetamorphosed volcanic rocks (Ireland Point Volcanics, Cooper, 1937; Williams, Smyth, and Stevens, 1973), or it transgresses upward to eliminate the aureole so that ultramafic rocks directly overlie lower structural slices, for example, Howe Harbour. It is clear then that the aureole of the White Hills Peridotite Sheet bears no genetic relationship to the present tectonic base of the thrust slice that includes the aureole and the ultramafic rocks.

Widely-separated occurrences of aureole rocks in separate sub-horizontal slices are also known north of Hare Bay at Quirpon Island, at Savage Cove 1.6 km southwest of Cape Onion, and along the shoreline of a large lake 8 km southeast of Raleigh. These rocks were presumably also once overlain by peridotites that formed part of the same structural slices and that were since removed by erosion. Similarly, northeast of Goose Cove at Three Mountain Summits, an amphibolite outlier surrounded by greenschists forms the tops of the highest hills, implying that peridotites were also once present in this locality and since removed by erosion.

South of Hare Bay, steeply-dipping amphibolites and greenschists that are identical to the White Hills occurrences constitute Fishot Islands, and a positive offshore magnetic anomaly suggests the presence of submerged peridotite seaward from the amphibolites (Canada Geol. Survey, Map 7366G, 1970). Sixteen km farther south, a small slice of greenschist and amphibolite occurs at Croque Head.

At Milan Arm, amphibolite outcrops up to 30 m in diameter are partly surrounded by thin (0.6-1.2 m) rodingite alteration haloes, in turn surrounded by black serpentinite. These metamorphic rocks in places include coarse-grained hornblende-biotite schists and exceedingly coarse-grained hornblendites, diorites, and pyroxenites, locally with single pyroxene crystals exceeding 15 cm in length. The structural relationships of the Milan Arm amphibolites to nearby occurrences of ultramafic rocks are unknown, and because the rocks in this locality appear to be much dismembered they are thought to represent, at least in part, large outcrop-size blocks in a shaly mélange.

Finely-banded, hard, recrystallized ultramafic rocks underlie schistose serpentinized peridotites of the White Hills at the shoreline on the eastern side of Howe Harbour. There, the present tectonic base of the White Hills slice (zone of emplacement) is essentially coincident with the base of the ultramafic rocks or zone of earliest transport or displacement. A few meters of rodingite overlain by 6 m of brecciated serpentinite occur above black shales that have a flat cleavage in the contact zone. The finely-banded rocks, which overlie the brecciated serpentinite, were at first thought to be a part of the amphibolite aureole, but the rocks are clearly of ultramafic derivation as evidenced by attenuated relict orthopyroxenes with glide lamellae and chromite and ceylonite, which are all characteristic of the ultramafic rocks elsewhere and which are unknown in the aureole amphibolites. The thinest bands are lenticular and less than 0.3 cm thick and alternate with wider and more persistent bands up to 5 cm thick. Approximately 1.5 m of the finely-banded rocks are exposed, and their common occurrence as beach cobbles in this area suggests a greater extent. The rocks have a distinct foliation parallel to the banding that is portrayed by the parallel alignment of both metamorphic minerals and relict orthopyroxenes. Leucocratic bands consist of deep brown hornblende, colorless clinopyroxene, brown biotite, and garnet (?), and these bands alternate with darker serpentine rich bands. Similar rocks occur at the base of a small outlier west of St. Anthony, and comparable hard thin bands occur in serpentinized ultramafics of the Bay of Islands Complex within a few tens of meters above the amphibolite aureole at North Arm and Trout River Pond.

*Lithology.*—The aureole of the White Hills Peridotite Sheet is comprised mainly of greenschists, approximately 180 m thick, that are overlain by approximately 90 m of amphibolites and pyroxene-bearing amphibolites. The contact between the peridotites and the aureole is in most places marked by a topographic depression of no exposure; however, a contact zone from 10 to 30 m thick can be defined in the rocks nearest the peridotites by the presence of deep brown hornblende and augite. From top to bottom across this contact zone, the hornblende exhibits decreasing intensity of pleochroism from deep reddish brown to pale greens, and this variation is accompanied by a decrease in the anorthite content of associated plagioclase (Tuke, 1968). The pyroxene-bearing amphibolites are in places banded in this contact zone. Elsewhere outside the contact zone, the amphibolites are well-foliated amphibolite-plagioclase schists, locally garnetiferous and in places containing interlayers of hornblende–biotite–garnet schist. At Fishot Islands, the amphibolites locally include thin (1 m) marble beds and lenses of metagabbro.

The amphibolites are gradational over several tens of meters into underlying greenschists by a decrease in grain-size of prismatic amphibole crystals accompanied by an increase in the amount of chlorite characteristic of the underlying greenschists. The gradational relationship is well exposed east of the Goose Cove road on the flanks of Three Mountain Summits.

The greenschists are best exposed in wave-washed outcrops at Goose Cove and northward. Most are finely laminated with thin alternating dark green and light green to buff laminae. Pre-tectonic schistose gabbro sills occur within the greenschists at Starks Bight, and post-tectonic mafic to intermediate dikes locally cut the greenschists elsewhere, especially at the headland east of Goose Cove.

A complete gradation between greenschists and schistose agglomerates is well-displayed at Starks Bight, and the schistose agglomerates grade westward into more massive agglomerates with associated relatively undeformed pillow lavas of the Ireland Point Volcanics. The latter in turn structurally overlies transported graywackes of the Maiden Point Formation.

*Structural features.*—Almost all the aureole rocks exhibit the effects of polyphase deformation, though this is most evident in the greenschists and amphibolites. The commonest structures are tight recumbent folds that clearly fold an earlier schistosity. Where the metamorphic rocks are banded near the peridotite contact, they do not display the recumbent folds. This banding parallels the peridotite contact and a tectonic fabric evidenced by attenuated orthopyroxenes in the overlying ultramafic rocks.

Commonly the aureole rocks near the contact possess a strong schistosity with knots and augen of hornblende and/or pyroxene enclosed in a feldspar-rich matrix. This foliation parallels the base of the White Hills Peridotite Sheet and also the axial planes of recumbent second phase ($F_2$) folds that are well-developed in the underlying amphibolites. The fabric is therefore interpreted as a composite second phase schistosity ($S_2$) even though no recumbent $F_2$ folds are apparent in the pyroxene-bearing amphibolites.

Polydeformed amphibolites of the amphibolite zone everywhere display a marked foliation and grade downward into polydeformed greenschists. The intensity of deformation is zoned within the greenschists, and the rocks vary from semi-schists to intensely foliated schists. In the semi-schist areas, primary features of the rocks are retained, but elsewhere the rocks are converted to fine-grained well-foliated schists. The dominant fabric is a first phase schistosity ($S_1$) that is refolded about second phase west- to southwest-facing tight recumbent folds ($F_2$). Axial surfaces of the

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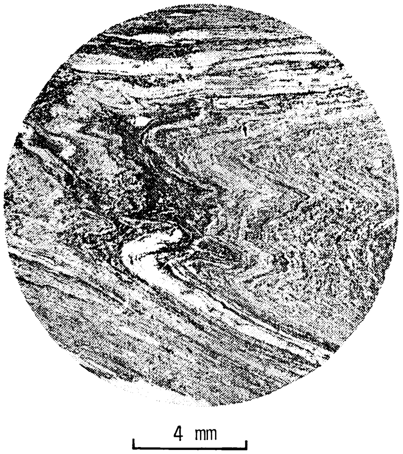

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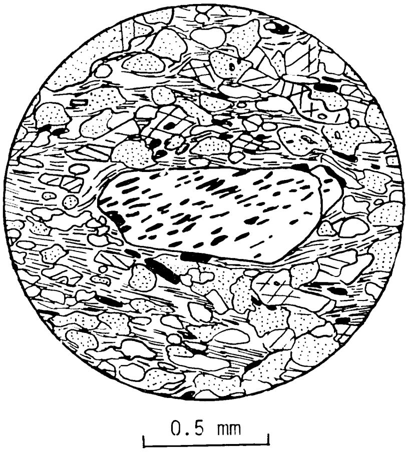

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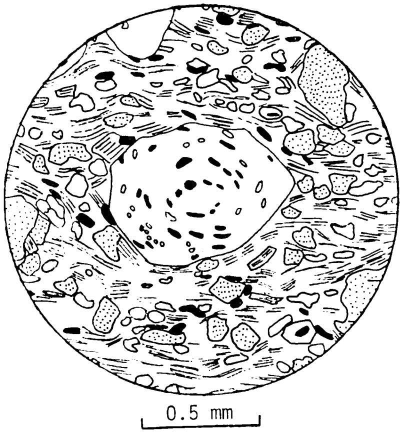

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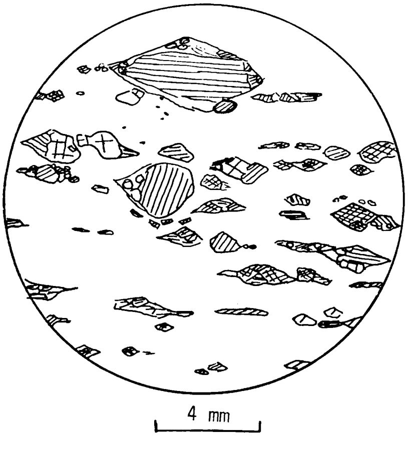

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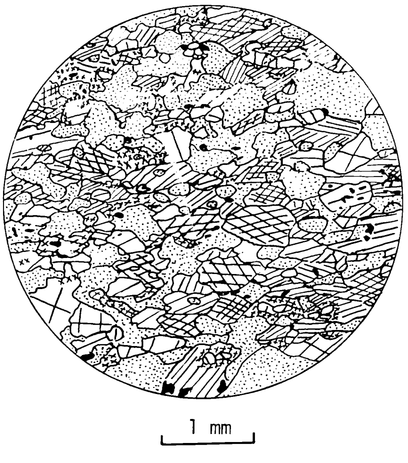

latter are gently-dipping, and in a gross regional way they parallel the prominent schistosity ($S_1$) and parallel the base of the White Hills Peridotite Sheet.

At Fishot Islands, the aureole rocks are also steeply-dipping, and they have been affected by a third phase of folding ($F_3$) that postdates the emplacement of the transported slices and that increases in intensity across the Hare Bay region from west to east. In this more easterly area then, an initially subhorizontal thrust slice was tilted eastward by post-emplacement deformation.

*Metamorphic history.*—Three regional metamorphic mineral assemblages that coincide with three distinct lithological subdivisions are recognized within the aureole. These are (A) chlorite–albite–epidote–muscovite–tremolite–actinolite of the greenschist facies, (B) green hornblende–plagioclase ($An_{36-38}$) or quartz–biotite–garnet–plagioclase ($An_{36-38}$) of the amphibolite facies, and (C) brown hornblende–plagioclase ($An_{38-40}$)–augite typical of the upper amphibolite facies.

The dominant fabric elements of the aureole rocks are first and second phase schistosities ($S_1$ and $S_2$). The second phase schistosity ($S_2$) is clearest in the amphibolites, and it diminishes structurally downward where the first phase schistosity ($S_1$) is in places the only recognizable fabric in the underlying greenschists. The first phase schistosity ($S_1$) is folded around recumbent $F_2$ folds that have large amplitudes compared to their wavelengths (for example, fig. 4A). It has been possible to relate the growth of the metamorphic minerals to these deformation events ($D_1$ and $D_2$) using textural methods as described by Zwart (1960) and Spry (1969). The main crystallization event in the greenschists is syntectonic with the first deformation ($D_1$), but in the amphibolites crystallization continued through to the second deformation ($D_2$).

In the greenschists $D_1$ syntectonic crystallization led to the growth of fine-grained tremolite-actinolite, chlorite, and epidote that have a strong preferred orientation and that define the $S_1$ schistosity. Plagioclase

Fig. 4. Aureole textures

A. $F_2$ fold in greenschist folding $S_1$ schistosity defined by aligned chlorite and epidote (dark bands), tremolite–actinolite, quartz and plagioclase (light bands), quartz-rich bands (clear), and opaques (thin black bands). Greenschist, North Arm, Bay of Islands.

B. and C. Straight $S_1$ inclusion trains in garnet porphyroblasts indicating static growth of garnet following the first deformation. Biotite and hornblende form a second schistosity around the earlier garnet and plagioclase porphyroblasts. B, garnetiferous amphibolite, Fishot Island; C, garnetiferous amphibolite, North Arm, Bay of Islands.

D. Circular inclusion train in garnet indicating static growth. The garnet predates the $S_2$ biotite fabric that forms augen around it. Amphibolite, Fishot Island.

E. Augen-shaped pyroxene and hornblende porphyroblasts in a fine-grained plagioclase and quartz matrix (clear). The matrix shows a dimensional preferred orientation. Eastern White Hills, 2.5 m from contact.

F. Pyroxene-bearing amphibolite showing fabric that parallels the contact with overlying peridotite. Western White Hills, 3 m from the contact.

Garnet, heavy outline and clear; plagioclase, stippled; quartz, light outline and clear; biotite, hatched; hornblende, closely spaced cleavages; pyroxene, widely spaced cleavages; ores, black. All line drawings from photomicrographs.

($An_{8\text{-}12}$) growth accompanied this event. In the amphibolites, aligned biotite and hornblende define the $S_1$ schistosity.

Post-tectonic crystallization with respect to the first deformation is of minor importance in the greenschists but is extensive in the amphibolites. In the greenschists it is marked by rare, randomly oriented crystals of tremolite-actinolite and epidote that overgrow the $S_1$ fabric. In the amphibolites $D_1$ post-tectonic crystallization is marked by porphyroblastic growth of garnet and plagioclase ($An_{36\text{-}40}$). Some of the garnets overgrew and include the $S_1$ fabric (fig. 4B). However, more commonly the inclusions are arranged in a number of concentric rims that mimic the hexagonal shape of the porphyroblasts (fig. 4D). This inclusion pattern is believed to be the result of rapid static growth that engulfed impurities concentrated at the advancing grain boundaries. The plagioclase porphyroblasts are generally inclusion-free, but in a few places they contain both oriented and unoriented biotite flakes.

$D_2$ syntectonic growth is restricted in the greenschists to the psammitic and semi-pelitic rock types where oriented chlorite and muscovite define the $S_2$ schistosity. In the amphibolites, $S_2$ schistosity is characterized by the growth of biotite in the pelitic rocks and by hornblende within metavolcanic rocks. The $S_2$ schistosity outlines augen around the garnet and plagioclase porphyroblasts (fig. 4B, D), clearly indicating that the growth of these porphyroblasts preceded the $D_2$ deformation. In a few places, garnets show narrow $D_2$ overgrowth zones that contain curved inclusion trails in the $D_2$ growth portions. In the aureole rocks near the peridotite contact, pyroxene and deep brown hornblende define a strong $S_2$ schistosity (fig. 4E, F) and plagioclase ($An_{40}$) is developed parallel to this fabric.

Post $D_2$ retrograde metamorphism of the aureole rocks is widespread but not strongly developed. Feldspar is sericitized and saussuritized, biotite is altered to chlorite, pyroxene is retrogressed to hornblende, and hornblende to tremolite-actinolite. Annealing of quartz and feldspar to produce polygonal textures in the contact zone is also a post-tectonic event.

At Fishot Islands, where the aureole rocks were affected by post-emplacement Devonian (Acadian) deformation, there is no indication of metamorphic mineral growth accompanying this event, although there has been quartz recrystallization in kink bands and local retrogression of biotite to chlorite.

*Protoliths.*—Gradational relationships between amphibolites of the aureole through greenschists of identifiable protolith, into relatively undeformed and unmetamorphosed rocks, give some idea of the rock types from which the aureole was formed. Most of the greenschists are finely-laminated rocks sugesting a tuffaceous origin, and this is locally confirmed by the presence of thin graded units exposed in rock cuts near the village of Goose Cove South. Three km north of Goose Cove, the greenschists include coarse tuff and agglomerate as clearly indicated by stretched volcanic fragments in a schistose grayish green matrix, and in a few places poorly preserved pillows indicate that mafic flows were also a part of the protolith. Where the greenschists grade into the Ireland Point Volcanics at Starks Bight, the latter are mainly purple and green agglomerates and coarse tuffs, and similar rocks are dominant all along the north side of Hare Bay. In a few places, notably 1.5 km west of Starks Bight, the Ireland Point Volcanics includes well-preserved pillowed lava with gray-green bun-shaped pillows and with limestone present between the pillow interstices.

Sedimentary rock units are represented throughout the greenschists but are everywhere of minor extent. At Goose Cove and Starks Bight, the greenschists have infolded black pyrite-bearing pelitic units, thin recrystallized limestone bands, and local psammitic units up to several tens of meters in structural thickness. At Fishot Islands, the greenschists also include thin psammitic units, and similar rocks occur among the greenschists at nearby Pigeon and Great Verdon Islands.

A 9 m thick graywacke unit, similar in lithology to the Maiden Point Formation, underlies the greenschists along the west side of Fishot Islands. It has beds from 1 to 1.2 m thick at its base that are poorly graded and interbedded with red slate. Toward the top of the unit the graywacke beds are thinner, and they are interbedded with purple and green agglomerate and tuff. Similar graywackes form part of the White Hills structural slice south of Milan Arm.

A pre-tectonic gabbro sill occurs in the amphibolites at Fishot Islands, and other occurrences are known at Starks Bight and elsewhere in the vicinity of the White Hills.

The finely-banded recrystallized ultramafic rocks on the eastern side of Howe Harbour have not been described as part of the aureole, for they do not appear to form a uniform and persistent zone. However, those occurrences that are known, both in the White Hills and Bay of Islands areas, occur at or near the aureole contact at the base of the ultramafic units. Furthermore, the metamorphic recrystallization, banding, and foliation in the finely-banded rocks are all probably coeval with the development of the amphibolite aureole. If the finely-banded rocks are included as an integral part of the aureole, then of course the aureole would include ultramafic protoliths.

*Provenance.*—The graywackes at the base of the greenschists along the western side of Fishot Islands are lithologically similar to semi-schists of the Maiden Point Formation that occur in a separate slice at Croque Head. The Maiden Point is interpreted as a Lower Cambrian westerly-derived wedge of sediment built up along a continental margin in western Newfoundland (Stevens, 1970; Williams, Smyth, and Stevens, 1973). The dominant volcanic lithologies of the aureole could represent a more easterly volcanic rich facies of the Maiden Point, probably not unlike the Maiden Point presently exposed in the vicinity of St. Lunaire where agglomerates, tuffs, and pillow lavas are dominant over graywacke. Black pelitic units of the aureole such as those exposed at Goose Cove could correlate with similar rocks that are widespread throughout the Maiden Point Formation, for example, at Sacred Bay, or possibly they correlate with younger units such as the Northwest Arm Formation and its equivalents that are dominantly black and green, pelitic, and locally dated as Tremadocian.

The aureole of the White Hills Peridotite Sheet was, therefore, produced mainly from mafic volcanic rocks, dominantly fragmental, with local interbedded thin sedimentary units. The age and provenance of these rocks are uncertain, but several tenuous lines of evidence suggest that they are far-travelled correlatives of Cambrian-Lower Ordovician rocks in structurally lower, dominantly sedimentary, slices in the Hare Bay area.

Palinspastic restoration of the thrust slices in the Hare Bay area, according to the scheme that the highest structural slices are the farthest travelled requires that the White Hills Peridotite Sheet and its attached aureole in the highest structural slice together moved westward for a minimum distance of 80 km. The depositional regime of the aureole rocks therefore lay at least 80 km to the east.

## THE METAMORPHIC AUREOLE OF THE BAY OF ISLAND COMPLEX

*Distribution*—The aureole of the Bay of Islands Complex is exposed along the eastern sides of the four separate massifs that comprise the complex, namely, Lewis Hills, Blow-Me-Down Mountain, North Arm Mountain, and Table Mountain (fig. 3). Along the eastern margin of the three northernmost massifs, it forms a steeply-dipping narrow northeast-trending outcrop belt of uniform width (about 300 m) that is conformable with the ultramafic rocks at the stratigraphic base of the Bay of Islands ophiolite suite. The aureole is characterized by rugged bush-covered terrane so that complete sections are only visible in stream cut ravines. Where the base of the ultramafic unit and underlying garnetiferous amphibolites are well-exposed along the south shore of Trout River Pond, the gradational sequence of metamorphic rocks has been disrupted by faults so that garnetiferous amphibolites are now juxtaposed with relatively unmetamorphosed and undeformed mafic volcanic rocks. Along the eastern margin of the Lewis Hills massif, the aureole rocks form an abnormally wide belt (locally in excess of 1 km), suggesting that the aureole there has a subhorizontal attitude. This is further supported by the local presence of ultramafic outcrops within the belt of aureole rocks (Smith, 1958) that are probably outliers of the overlying Bay of Islands peridotites.

The sequence of ophiolite units at Blow-Me-Down Mountain, North Arm Mountain, and Table Mountain is disposed in synclines with northeast-trending subhorizontal axes and moderately to steeply-dipping limbs (fig. 3). Subhorizontal mélange zones or thrusts mark the present bases of these three northernmost massifs so that the steeply-dipping units of the ophiolite sequence and the aureole are all structurally truncated. The form of the Lewis Hills massif is less well known, but outcrop patterns suggest a more subhorizontal disposition of its rock units.

One km west of Stowbridge Head at North Arm Mountain, steeply-dipping aureole rocks are exposed at the base of the massif between serpentinized peridotite toward the east and an underlying sedimentary mélange zone above unmetamorphosed clastic sedimentary rocks of the Blow-Me-Down Brook Formation (Williams, 1973) toward the west. One km east of Stowbridge Head, tectonic inclusions of garnetiferous amphibolite occur in serpentinite mélange at the base of North Arm Mountain.

Smith (1958) reported a narrow band of amphibolite in an anomalous position along the eastern side (top) of the Mount St. Gregory gabbro mass (North Arm Mountain), which he correlated with the basal aureole of the Bay of Islands Complex elsewhere. The Mount St. Gregory occurrence lies between gabbro and volcanic rocks that are now known to be separated by metamorphosed sheeted dikes or dike breccias (Williams and Malpas, 1972). Recent mapping in the Mount St. Gregory area failed to confirm Smith's report. Furthermore, rocks like those in the basal aureole are unknown above the gabbro unit of the Bay of Islands Complex elsewhere in the area. The report is therefore suspect, especially as the age relationships among the rocks at the top of the gabbro unit within the ophiolite sequence have now been reinterpreted (Williams and Malpas, 1972).

The aureole of the Bay of Islands Complex, therefore, occupies a constant stratigraphic level at the base of the ultramafic rocks of the ophiolite sequence of rock units, and, like the aureole of the White Hills Peridotite Sheet, it bears no relationship to the present structural base of the separate massifs. The absence of aureole rocks along the western margins of the individual massifs is the result of structural omission as the stratigraphically lowest ophiolite units are missing, and gabbro or else upper parts of the underlying ultramafic unit are the lowest rocks represented there.

*Lithology.*—The most accessible and continuous aureole exposures occur in stream valleys of North Arm Mountain at North Arm. The aureole there has a structural thickness of approximately 150 m and includes pyroxene-bearing amphibolite at the contact that grades downward into garnetiferous amphibolite, black amphibolite, greenschist, garnetiferous phyllite, and eventually dark gray argillite. The pyroxene-bearing rocks at the contact are rarely more than 3 m thick, and they are underlain by approximately 60 m of amphibolite, 60 m of greenschist, and about 30 m of garnetiferous phyllite. At Pond Point of North Arm, the greenschists and garnetiferous phyllites are locally in irregular splayed-faulted contact, and the garnetiferous phyllites grade eastward into relatively unmetamorphosed dark gray argillites with the tectonic base of the sequence unexposed.

Pyroxene-bearing amphibolites at the contact are light to dark gray and greenish gray medium-grained rocks that exhibit a compositional banding with bands 0.6 cm to 2.5 or 5 cm wide. Smith (1958) identified the pyroxene as diopside and noted a high anorthite content in the accompanying plagioclase ($An_{60-90}$). The hornblende in these contact rocks is pleochroic in deep reddish brown and exhibits decreasing intensity of pleochroism across the zone through pale browns to green. Calcium rich secondary minerals are common (prehnite, clinozoisite, xonotlite, calcite), and these probably relate to local metasomatism at the contact that accompanied post-emplacement serpentinization of the adjacent ultramafic rocks.

Underlying amphibolites consist of dark gray to black foliated rocks composed of hornblende and altered plagioclase. Garnet is common in the upper part of the zone nearest the overlying ultramafic rocks, and it decreases in abundance downward. The amphibolites grade into greenschists by a decrease in abundance and grain size of amphibole crystals accompanied by an increase in the amount of chlorite present. The chloritic rocks are everywhere schistose and polydeformed.

The outer phyllite zone is characterized by dark greenish gray to dark gray fine-grained to aphanitic schistose rocks. Porphyroblasts of garnet and quartz are visible in some hand specimens, and small garnets are common in most thin sections. The garnets are locally poikiloblastic, and they have been affected by subsequent chloritization in some places. These rocks are gradational with unmetamorphosed argillites at Pond Point.

One km west of Stowbridge Head, the aureole rocks are mainly banded garnetiferous amphibolites, but nearer the serpentinized peridotite contact they are brownish weathering, soft, and schistose and contain more than 50 percent pale red garnet porphyroblasts in a black matrix.

*Structural features.*—The aureole rocks vary from banded pyroxene-bearing amphibolites at the peridotite contact through polydeformed amphibolites and greenschists that exhibit numerous minor folds to phyllites and relatively undeformed argillites. The banded amphibolites do not exhibit minor folds, and the banding is regionally conformable to the aureole-peridotite contact. At the contact the peridotite is schistose, and this tectonic fabric in the plutonic rocks is also essentially parallel to the aureole-peridotite contact and to banding in adjacent amphibolites. There is a marked absence of intrusive relationships at the contact such as a chilled border zone in the ultramafic rocks, dikes, or apophyses of peridotite cutting the aureole rocks, or inclusions of aureole rocks in the peridotite. A serpentinite "projection" capped by unmetamorphosed sedimentary rocks at Shoal Brook (Smith, 158, p. 17) has now been re-interpreted as a serpentinite block or knocker in a sedimentary mélange that marks a later contact of gravity sliding.

Amphibolites and greenschists of the aureole at North Arm exhibit a marked early foliation ($S_1$) that is deformed by second phase folds ($F_2$). The second phase folds locally display an axial planar second schistosity ($S_2$), and the axial surfaces of the second phase folds usually parallel the steeply-dipping peridotite-aureole contact, indicating that they originated as recumbent structures beneath the ophiolite sequence. Phyllites or argillites nearby have a composite or single schistosity that also parallels the attitude of the peridotite-aureole contact. Neither the ophiolite suite nor the aureole rocks exhibit any minor structures that relate to the regional synclinal form of the ophiolites, except possibly for a strain slip cleavage in the sediments at Pond Point. This open folding of the ophiolite succession was the latest deformation to affect these rocks, although it predated the final emplacement of the ophiolite slice.

*Metamorphic history.*—Petrographic thin-section examination of several representative lithologies across the aureole of the Bay of Islands Complex at North Arm indicates exactly the same structural style, metamorphic facies, and metamorphic crystallization history as that exhibited in the aureole of the White Hills Peridotite Sheet.

A contact zone of banded amphibolites with deep brown hornblende in the Bay of Islands aureole is in most respects identical to that in the White Hills Peridotite Sheet aureole. Similarly the amphibolite and greenschists zones have their counterparts of comparable thickness in each of the widely separated areas.

In the Bay of Islands aureole, as in the White Hills Peridotite Sheet aureole, the main schistosity in the amphibolites ($S_2$) is associated with the second deformation ($D_2$) and diminishes structurally downward. Garnet porphyroblasts overgrew an earlier schistosity ($S_1$), and they are augen-shaped and surrounded by the $S_2$ schistosity (fig. 4C). In the underlying greenschists the main schistosity ($S_1$) is associated with the first deformation ($D_1$), and it is folded about second phase folds ($F_2$) (fig. 4A).

*Protoliths.*—The main lithologies and metamorphic mineral assemblages represented in the Bay of Islands aureole are identical to those of the aureole beneath the White Hills Peridotite Sheet. However, the volcanic protoliths, so common among the greenschists at Hare Bay, are unknown in the Bay of Islands, and psammitic units, like those exposed at Fishot Islands, and limestone and marble bands are also unknown in the southern area.

Where the greenschist facies aureole rocks of the Bay of Islands Complex grade outward into relatively unmetamorphosed rocks at Pond Point, the gradation is between garnetiferous phyllite and its protolith, that is, dark gray to black argillite. However the similarities elsewhere among the aureole rocks of both areas demand that the volcanic protoliths like those of the Hare Bay area are the dominant lithologies from which the Bay of Islands aureole was derived.

The absence of identifiable volcanic rocks in the Bay of Islands aureole and the preponderance of regionally surrounding psammitic rocks (although for the most part in lower structural slices) suggested to Smith (1958, p. 19) that the aureole rocks were the result of lime and magnesia metasomatism at the ultramafic contact. There is no need to appeal to metasomatism, however, if the protoliths of the aureole rocks are mafic volcanics as is clearly indicated by the relationships in the Hare Bay area.

*Provenance.*—The age and depositional site of the metamorphic aureole rocks of the Bay of Islands Complex are even less well-known than is this data for similar rocks in the Hare Bay area. Dark gray argillites, gradational with garnetiferous phyllites of the aureole at Pond Point, resemble the Middle Arm Point Formation (Stevens, ms; Williams, in press) of Lower Ordovician (Tremadocian) age represented in underlying sedimentary slices. However the Middle Arm Point Formation does not include mafic volcanic rocks which are inferred to be the chief protolith of the Bay of Islands aureole.

As in the case of the Hare Bay area, palinspastic restoration of the transported slices in the Bay of Islands area indicates that the aureole rocks, welded to the peridotites in the highest structural slice, moved westward for a minimum distance of 105 km.

## RATIONALE OF THE AUREOLES

Any attempt to rationalize the aureoles beneath the west Newfoundland ophiolite complexes must explain the following:

1. Lack of intrusive phenomena, that is, dikes, apophyses, inclusions, chilled border phase at the peridotite-aureole contact.
2. Localization of the aureole at a constant stratigraphic position at the base of the ophiolite suites where it underlies the thick ultramafic unit.
3. Decreasing metamorphism and intensity of deformation with depth beneath the peridotites.
4. Uniformly narrow width (everywhere less than 300 m structural thickness) along 55 km of exposed contact in the Bay of Islands region and a similar thickness beneath the areally extensive White Hills Peridotite Sheet.
5. Constant metamorphic lithologies implying similar protoliths.
6. Similar metamorphic zones of comparable widths in all localities clearly indicating uniform conditions of formation and a genetic relationship of all zones to the overlying peridotites.
7. Axial surfaces of recumbent folds and first ($S_1$) and second ($S_2$) generation schistosities parallel to the base of the ophiolite suite.
8. Tectonic fabrics in the aureole rocks indicating a stress field that coincided with a thermal aureole in both space and time so that the metamorphic textures produced are indistinguishable from those typical of regionally metamorphosed terranes.
9. A schistose zone in basal peridotites above the aureole that locally includes finely-banded recrystallized ultramafic rocks.
10. Banded, but unfolded, pyroxene amphibolites at the peridotite contact.
11. An aureole stamped upon mainly mafic fragmental volcanic rocks that were relatively undeformed and unmetamorphosed at the time, and which were probably deposited at or near a continental margin.

12. An aureole formed before subsequent westward transport of at least 80 to 105 km, mainly by gravity sliding tectonics.
13. An aureole unrelated to the present structural bases of the ophiolite slices.

It is clear from several of the foregoing prerequisites that the west Newfoundland aureoles cannot represent typcial hornfels at orthodox intrusive contacts. Particularly incongruous to such an interpretation are the special constant setting of the aureole, its narrow uniform width, its constant lithology, and its structural and metamorphic textural characteristics. However, a plate tectonic model that envisages the aureole as a result of the obduction of oceanic crust and mantle onto a continental margin seems to fit most of the requirements. According to this model supracrustal rocks are overridden by a subhorizontal sheet of forcefully expelled oceanic crust and mantle that is everywhere detached at approximately the same level, which in the case of the west Newfoundland examples is from 3 to 6 km within the mantle, that is, the thickness of the ultramafic unit of the ophiolite suite. The aureole would therefore evolve as a contact dynamo-thermal aureole and acquire its structural style and metamorphic zonation during the early stages of continuous, or possibly episodic, expulsion. Following the formation of the aureole, the ophiolite slice moved along a lower structural base so that the aureole was included as a structural underpinning welded against the basal peridotites. Subsequent transport was mainly effected by cold gravity sliding and the development of the characteristic mélange zones along which the sequences of transported slices in western Newfoundland were finally emplaced.

A plate tectonic model such as the above is attractive for it accommodates the features displayed by the aureole rocks, and its explains their special position at the base of the ophiolite suite. The structural style and metamorphic history of the rocks fit well with this interpretation: recumbent folds in greenschists and amphibolites with schistosity parallel to the basal peridotite contact are then related to horizontal translation of the oceanic crust-mantle slice, banded amphibolites at the peridotite contact probably represent recrystallized mylonites, and schistose peridotites with hard recrystallized bands above the aureole represent ultramafic rocks that originated as mantle tectonics but that were subsequently mylonitized, recrystallized, and serpentinized in the zone of actual obduction. The aureole rocks may include a wide range of lithologies according to this model, all structurally telescoped into a narrow zone during progressive obduction. The plate tectonic model therefore satisfies the field data and general considerations that require immediate solution.

The direction of the ridge upwelling at which the ophiolites were produced can be gleaned from the attitude of sheeted dikes in the transported complexes that were presumably parallel to the ridge when emplaced (Williams and Malpas, 1972). Furthermore the direction of earliest transport of the ophiolites with respect to the direction of the ridge can be ascertained by comparing the attitude of sheeted dikes with the direction of transport indicated by the vergence and facing direction of early recumbent structures in the aureole rocks. The implications of these comparisons await the results of studies in progress.

Two major problems remain. Firstly, the mechanics of displacing oceanic crust and mantle onto a continental margin are either completely unknown, or at most, poorly understood. Secondly, it seems unlikely that a far-travelled oceanic crustal slab could reach the supracrustal level of the aureole protoliths and retain sufficient heat to effect thermal metamorphism. If it could not, then the heat must be the product of friction and work done in the zone of expulsion and translation. Dissemination of heat by downward conduction presumably established the required temperature-distance relationship for the metamorphic zonation of the rocks. Of course, the heat source, the factors controlling heat distribution, and the attitude of geoisotherms are all recurring problems in most analyses of regionally metamorphosed terranes, and whether or not the above model is tenable rests largely upon these poorly understood considerations.

## DISCUSSION

The Bay of Islands Complex is one of the clearest examples in the world of an on-land complete ophiolite suite. Yet it would appear from a review of the literature that few analogous ophiolite complexes are characterized by comparable metamorphic aureoles. The authors do not feel that the Bay of Islands aureole represents a unique situation, but rather that similar aureoles are absent elsewhere through structural omission, or where present, they have been interpreted in different ways by different workers so that the inherent similarities are not readily apparent.

Directly comparable to the Bay of Islands Complex in completeness and geologic setting are the Semail nappe of Oman (Reinhardt, 1969), the Papuan nappe of New Guinea (Davies and Smith, 1971), and ultramafic plutons of New Caledonia (Avias, 1967). Neither has an attached aureole of the Bay of Islands type, but a few similarities are worthy of mention.

Exotic amphibolites with deep brown hornblende and garnet porphyroblasts occur among strongly laminated metamorphic rocks in a discontinuous thin sheet at the base of the Semail nappe (Reinhardt, 1969). Some of the metamorphic rocks grade into recognizable sediments and volcanics, but the amphibolites are "enigmatic" (p. 22), and they "could be derived in solid state from great depth" (p. 24). These Oman amphibolites are probably direct analogues of the west Newfoundland examples, and they probably have the same significance where they occur in a similar tectonic setting at the base of an on-land ophiolite sequence.

Regional metamorphism in the Owen-Stanley Range is thought to be directly related to the emplacement of the ophiolites of the Papuan nappe (Davies and Smith, 1971, p. 3307). This is an extensive metamorphic terrane that locally includes high pressure facies series assemblages such as lawsonite and glaucophane-bearing schists. However, greenschists, amphibolites, and hornblende-pyroxene granulites are common elsewhere, for example, D'Entrecasteau Islands, and amphibolites and hornblende granulites are recorded in upper parts of the section and near the base of the Papuan nappe near the Owen-Stanley Fault (Davies and Smith, 1971). Possibly some of these rocks are analogous to the west Newfoundland metamorphic aureoles.

Synkinematic and contemporaneous greenschist and blueschist facies occur at New Caledonia, and the juxtaposition of the metamorphic belt with large ultramafic bodies implies a tectonic relationship between metamorphism and emplacement of the ultramafic masses (Coleman, 1967). More recently, blueschists have also been recognized in the Oman Mountains (R. G. Coleman, personal commun., 1972).

Examples of polydeformed metamorphic rocks that locally border ultramafic plutons of the Klamath Mountains and Northern Sierras of California are in many respects similar to the Newfoundland examples. Coarse-grained hornblende gneiss that grades downward into hornblende schist occupies a narrow belt adjacent to the lower contact of the Trinity ultramafic sheet for at least 12 km (Lipman, 1964). It is unlikely that the ultramafic rocks were emplaced "along a regional metamorphic horizon of atypical high grade" (p. 217), and this suggestion would be still more incongruous in the case of the west Newfoundland examples. Metamorphic rocks occur at the base of the nearby Seiad ultramafic complex (L. G. Medaris, personal commun., 1972), and metamorphic rocks of higher than average grade surround several other ultramafic bodies in the Klamath Mountains (G. A. Davis, personal commun., 1972).

The Feather River ultramafic pluton of the northern Sierra Nevada Mountains has a polydeformed amphibolite metamorphic terrane along its western margin, which in roadside outcrops is lithologically and structurally similar to the west Newfoundland aureole rocks. The Canyon Mountain Complex (Thayer, 1963) of adjoining Oregon State does not have an exposed basal aureole, but large amphibolite blocks in mélange beneath the pluton probably represent aureole rocks that were dismembered during transport and emplacement.

The Vourinos ophiolite complex, northern Greece, locally has a 2 m-thick layer of quartz-garnet amphibolite at its base that grades downward and away from the contact into phyllite and quartz-sericite schist (Moores, 1969, p. 10). Other Tethyan examples, for example, the Troodos massif, have metamorphic rocks at the base of thrust-slices (J. G. Malpas, personal commun., 1972). Where metamorphic rocks occur elsewhere the relationships are rarely clear, so that the metamorphic rocks may be in separate slices rather than in aureoles welded to the ultramafic rocks.

The Brezovica ultramafic sheet (Karamata, 1968) outcrops as erosional remnants of a once-continuous body with each surrounded in map-pattern by an underlying subhorizontal aureole. This example from the Vardar zone of the Yugoslavian Dinarides appears to be identical in gross aspect to the White Hills Peridotite Sheet. Metamorphic zonation and the width of the metamorphic zones are comparable in both areas, and in each case the prototypes were unmetamorphosed supracrustal rocks.

At Unst and Fetlar, the northernmost of the Shetland Islands (Scotland), two transported slices of serpentinized peridotite and dunite overlain by pyroxenites and greenstones are separated from each other and from an underlying basement complex by chatoic structural zones or "shuppen zones" (Flinn, 1958). This succession of igneous rock units is typical of the ophiolite suite. Hornblende schists (Norwick Hornblende Schists) are associated with the transported rocks and are commonest as discontinuous lenticular bodies in the shuppen zone at the base of the lowermost ophiolitic slice. The Norwick Schists possibly represent part of a metamorphic aureole beneath the westerly transported ophiolites, and their occurrence in the shuppen zones at the present structural bases of the transported slices indicates that in this example from the British Caledonides both the zones of early displacement and final emplacement are roughly coincident.

Church and Stevens (1970a, 1970b, 1971) have pointed out that the high temperature contact of the Bay of Islands Complex suggests comparisons with the Lizard (Green, 1964), Tinaquillo (MacKenzie, 1960), Beni Bouchera (Kornprobst, 1969), Sesia Lanzo (Nicolas, 1968), La Ronda (Loomis, 1972), and Mount Albert (Smith and MacGregor, 1960). However, none of these display a clear sequence of ophiolite units, and they are of contrasted geologic setting so that different interpretations are possible, for example, La Ronda has been interpreted as a mantle-derived diapir that penetrated the continental lithosphere by vertical tectonics (Loomis, 1972). Yet it is at least plausible that the Lizard represents a transported ophiolite complex, complete with metamorphic aureole of the Bay of Islands type, but in this example most of the rocks are so highly deformed that critical relationships are largely destroyed. Similarly the aureole at Mount Albert of Gaspé, Quebec, which borders only one side of the ultramafic pluton, may be analogous to the western Newfoundland examples.

Elsewhere in the western Appalachians, small ultramafic plutons in Vermont have been interpreted as mantle-derived and tectonically emplaced upward through continental crust (Chidester and Cady, 1972). Larger ultramafic plutons in the eastern townships of Quebec, northeastward along strike from the Vermont locality, that were traditionally thought of as crustal intrusions or else differentiated submarine flows (Lamarche, 1972) are now interpreted as transported oceanic crust and mantle (Laurent, 1973; St. Julien, 1973). These examples do not exhibit aureoles of the west Newfoundland type except possibly for the Thetford Mines pluton which locally has schistose garnet amphibolite at its lower contact (Laurent 1973).

It would appear then that Alpine peridotites are closely associated with attached or adjacent belts of metamorphic rocks. Aureoles welded to the ultramafics are critical in tectonic syntheses, especially so where the aureoles occur at the base of obviously transported complete ophiolite suites.

If the west Newfoundland ophiolite complexes and their aureoles are representative of a model of transported on-land oceanic crust and mantle as is indicated by their clear succession of ophiolite units (Williams and Malpas, 1972), then the authors feel that aureoles like those developed in western Newfoundland should be commonplace elsewhere. Future studies of metamorphic aureoles and detailed world-wide comparisons should provide an interesting insight into the total relationships of these metamorphic rocks to nearby rocks and the mechanisms of ophiolite transport and emplacement.

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## REFERENCES

Aumento, R., Loncarevic, B. D., and Ross, D. T., 1971, Hudson geotraverse: geology of the Mid-Atlantic Ridge at 45°N: Royal Soc. London Philos. Trans., v. A268, p. 623-650.

Ave'Lallemant, Hans, and Carter, N. L., 1970, Syntectonic recrystallization of olivine and modes of flow in the upper mantle: Geol. Soc. America Bull., v. 81, p. 2203-2220.

Avias, J., 1967, Overthrust structure of the main ultrabasic New Caledonian massives: Tectonophysics, v. 4, p. 531-541.

Bailey, E. H., Blake, M. C., Jr., and Jones, D. L., 1970, On-land Mesozoic oceanic crust in California Coast Ranges: U.S. Geol. Survey Prof. Paper 700-C, p. C70-C81.

Challis, G. A., 1965, The origin of New Zealand ultramafic intrusions: Jour. Petrology, v. 6, no. 2, p. 322-364.

Chidester, A. H., and Cady, W. M., 1972, Origin and emplacement of alpine-type ultramafic rocks: Nature Phys. Sci., v. 240 (Nov. 13), p. 27-31.

Church, W. R., 1972, Ophiolite: its definition, origin as oceanic crust and mode of emplacement in orogenic belts, with special reference to the Appalachians: Canada Dept. Energy, Mines, and Resources, Earth Physics Branch Pub., v. 42, no. 3, p. 71-85.

Church, W. R., and Stevens, R. K., 1970a, Mantle peridotite and the early Paleozoic ophiolite complexes of the Newfoundland Appalachians: Univ. Western Ontario Dept. Geology Contr., Prelim. Rept. no. 175.

———— 1970b, Mantle peridotite and early Paleozoic ophiolite complexes of the Newfoundland Appalachians [abs.]: Internat. Symposium Mechanical Properties and Processes in the mantle, Flagstaff ,Arizona, 1970, Program and Abstracts.

———— 1971, Early Paleozoic ophiolite complexes of the Newfoundland Appalachians as mantle-oceanic crust sequences: Jour. Geophys. Research, v. 76, p. 1460-1466.

Coleman, R. G., 1967, Glaucophane schists from California and New Caledonia: Tectonophysics, v. 4, p. 479-498.

———— 1971, Plate tectonic emplacement of upper mantle peridotites along continental edges: Jour. Geophys. Research, v. 76, p. 1212-1222.

Cooper, J. R., 1936, Geology of the southern half of the Bay of Islands Igneous Complex: Newfoundland Dept. Nat. Resources, Geol. Sec. Bull. 4, 62 p.

———— 1937, Geology and mineral deposits of the Hare Bay area: Newfoundland Dept. Nat. Resources, Geol. Sec. Bull. 9, 36 p.

Davies, H. L., and Smith, I. E., 1971, Geology of Eastern Papua: Geol. Soc. America Bull., v. 82, p. 3299-3312.

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

Dickey, J. S., Jr., 1970, Partial fusion products in alpine-type peridotites: Serrania de La Ronda and other examples: Mineralog. Soc. America Spec. Paper 3, p. 33-49.

Flinn, Derek, 1958, On the nappe structure of North-east Shetland: Geol. Soc. London Quart. Jour., v. 114, p. 107-136.

Green, D. H., 1964, The metamorphic aureole of the peridotite at the Lizard, Cornwall: Jour. Geology, v. 72, p. 543-563.

Hess, H. H., 1955, Serpentines, orogeny and epeirogeny, *in* Poldervaart, Arie, ed., Crust of the Earth: A symposium: Geol. Soc. America Spec. Paper 62, p. 391-407.

Jackson, E. D., and Thayer, T. P., 1972, Some criteria for distinguishing between stratiform, concentric and alpine peridotite–gabbro complexes: Internat. Geol. Cong., 24th, Montreal Canada, 1972, sec. 2, p. 289-295.

Karamata, S., 1968, Zonality in contact metamorphic rocks around the ultramafic mass of Brezovica (Serbia, Yugoslavia): Internat. Geol. Cong., 23rd, Prague, 1968, Proc., sec. 1, p. 197-207.

Kornprobst, J., 1969, Le massif ultrabasique de Béni Bouchera (Rif Interne, Maroc): Etude des péridotites de haute température et de haute pression, et des pyroxenolites, à grenat ou sans grenat, qui leur sont associées: Contr. Mineralogy Petrology, v. 23, p. 283-322.

Lamarche, R. Y., 1972, Ophiolites of Southern Quebec: Canada Dept. Energy, Mines, and Resources, Physics Branch Pub., v. 42, no. 3, p. 65-69.

Laurent, Roger, 1973, The Thetford Mines ophiolite, Paleozoic "flake" of oceanic lithosphere in the Northern Appalachians of Quebec [abs.]: Geol. Soc. America, Northeast Sec. Mtg. Program (Allentown, Pa., March), p. 188.

Le Pichon, Xavier, 1969, Models and structure of the oceanic crust: Tectonophysics, v. 7, p. 385-401.

Lipman, P. W., 1964, Structure and origin of an ultramafic pluton in the Klamath Mountains, California: Am. Jour. Sci., v. 262, p. 199-222.

Loomis, T. P., 1972, Diapiric emplacement of the Ronda high-temperature ultramafic intrusion, Southern Spain: Geol. Soc. America Bull., v. 83, p. 2475-2496.

MacGregor, I. D., ms 1964, A study of the contact metamorphic aureole surrounding the Mount Albert ultramafic intrusion: Ph.D. thesis, Princeton Univ., 195 p.

MacKenzie, D. B., 1960, High-temperature alpine-type peridotite from Venezuela: Geol. Soc. America Bull., v. 71, p. 303-318.

Malpas, John, Stevens, R. K., and Strong, D. F., 1973, The origin and significance of ophiolite-amphibolite associations [abs.]: Geol. Soc. America, Northeast Sec. Mtg. Program (Allentown, Pa., March), p. 192.

McTaggart, K. C., 1971, On the origin of ultramafic rocks: Geol. Soc. America Bull., v. 82, p. 23-42.

———— 1972, On the origin of ultramafic rocks: Reply: Geol. Soc. America Bull., v. 83, p. 3161-3162.

Medaris, L. G., Jr., 1972, High pressure peridotites in Southwestern Oregon: Geol. Soc. America Bull., v. 83, p. 41-58.

Moores, E. M., 1969, Petrology and structure of the Vourinos ophiolitic complex of Northern Greece: Geol. Soc. America Spec. Paper 118, 74 p.

———— 1970, Ultramafics and orogeny, with models of the U.S. Cordillera and the Tethys: Nature, v. 228, p. 837-842.

Moores, E. M., and Raymond, L. A., 1972, On the origin of ultramafic rocks: Discussion: Geol. Soc. America Bull., v. 83, p. 3157-3160.

Nicolas, A., 1968, Relations structurales entre le massif ultrabasiques de Lanzo, ses satellites et la zone de Sesia Lanzo: Schweizer. min. pet. Mitt., v. 48, p. 145-156.

———— 1969, Une vue unitaire concernant l'origine des massifs ultrabasiques des Alpes occidentales internes: Acad. sci. Paris Comptes rendus, v. 269, p. 1831-1834.

Nicolas, A., Bouchez, J. L., and Boudier, F., 1972, Interpretation cinematique des deformations plastiques dans le massif de lherzolite de Lanzo (Alpes Piemontaises) —comparison avec d'autre massifs: Tectonophysics, v. 14, p. 143-171.

Reinhardt, B. M., 1969, On the genesis and emplacement of ophiolites in the Oman Mountains geosyncline: Schweizer. min. pet. Mitt., v. 49, p. 1-30.

Smith, C. H., 1958, Bay of Islands Igneous Complex, Western Newfoundland: Canada Geol. Survey Mem. 290, 132 p.

Smith, C. H., and MacGregor, I. D., 1960, Ultrabasic intrusive conditions illustrated by the Mount Albert ultrabasic pluton, Gaspé, Quebec [abs.]: Geol. Soc. America Bull., v. 71, p. 1978.

Smyth, W. R., 1971, Stratigraphy and structure of part of the Hare Bay Allochthon, Newfoundland: Geol. Assoc. Canada Proc. (A Newfoundland Decade), v. 24, p. 47-57.

Spry, Alan, 1969, Metamorphic textures: London, Pergamon Press, 350 p.

Stevens, R. K., ms, 1965, Geology of the Humber Arm, West Newfoundland: M.Sc. thesis, Memorial Univ. Newfoundland.

———— 1968, Taconic klippen of Western Newfoundland: Canada Geol. Survey Paper 68-1, Pt. A, p. 8-10.

———— 1970, Cambro-Ordovician flysch sedimentation and tectonics in West Newfoundland and their possible bearing on a proto-Atlantic ocean: Geol. Assoc. Canada Spec. Paper 7, p. 165-177.

Stevens, R. K., and Williams, Harold, 1973, The emplacement of the Humber Arm allochthon, Western Newfoundland [abs.]: Geol. Soc. America, Northeast Sec. Mtg. Program (Allentown, Pa. March), p. 222.

St. Julien, Pierre, 1973, Structural setting of the Thetford-Mines ophiolitic complex [abs.]: Geol. Soc. America Northeast Sec. Mtg. Program (Allentown, Pa., March) p. 215.

Thayer, T. P., 1960, Some critical differences between alpine-type and stratiform peridotite-gabbro complexes: Internat. Geol. Cong., Copenhagen, 21st Sess. Rept., Pt. 13, p. 247-259.

———— 1963, The Canyon Mountain Complex, Oregon, and the alpine mafic magma stem: U.S. Geol. Survey Prof. Paper 475a, p. C82-C85.

Tuke, M. J. 1968, Autochthonous and allochthonous rocks in the Pistolet Bay area in Northernmost Newfoundland: Canadian Jour. Earth Sci., v. 5, p. 501-513.

Upadhyay, H. D., Dewey, J. F., and Neale, E. R. W., 1971, The Betts Cove ophiolite complex, Newfoundland: Appalachian oceanic crust and mantle: Geol. Assoc. Canada Proc. (A Newfoundland Decade), v. 24, p. 27-34.

Varne, R., and Rubenach, M. J., 1972, Geology of Macquarie Island and its relationship to oceanic crust, *in* Hayes, D. E., ed., Antarctic Oceanology 11: Antarctic Research Ser., Australian-New Zealand Sector, v. 19, p. 251-266.

Williams, Harold, 1971, Mafic-ultramafic complexes in Western Newfoundland Appalachians and the evidence for their transportation: a review and interim report: Geol. Assoc. Canada Proc. (A Newfoundland Decade), v. 24, p. 9-25.

Williams, Harold and Malpas, John, 1972, Sheeted dikes and brecciated dike rocks within transported igneous complexes, Bay of Islands, Western Newfoundland: Canadian Jour. Earth Sci., v. 9, p. 1216-1229.

Williams, Harold, Malpas, John, and Comeau, R., 1972, Bay of Islands map-area, Newfoundland: Canada Geol. Survey, Paper 72-1, Part A, p. 14-17.

Williams, Harold, Smyth, W. R. and Stevens, R. K., 1973, Hare Bay Allochthon, Northern Newfoundland: Canada Geol. Survey, Paper 73-1, Part A, p. 8-14.

Williams, Harold, 1973, Bay of Islands, map-area, Newfoundland: Canada Geol. Survey Paper 72-34.

Zwart, H. F., 1960, Relations between folding and metamorphism in the central Pyrenees and their chronological succession: Geologie Minjnb., v. 39, p. 163-180.