Olivine fabrics in the Bay of Islands Ophiolite: implications for oceanic mantle structure and anisotropy

MATTHEW H. SALISBURY[1]

Deep Sea Drilling Project and Geological Research Division, Scripps Institution of Oceanography, University of California, La Jolla, CA 92093, U.S.A.

AND

NIKOLAS I. CHRISTENSEN

Department of Geosciences, Purdue University, West Lafayette, IN 47907, U.S.A.

Received June 10, 1984

Revision accepted March 29, 1985

Petrofabric analysis of oriented ultramafic and mafic rock samples from six traverses representing all four massifs of the Bay of Islands ophiolite complex, Newfoundland, indicate that the ultramafic rocks are tectonites displaying fabrics consistent with high-temperature plastic flow on the olivine (010) [100] and (0*kl*) [100] slip systems. The fabric orientation is uniform in three of the four massifs but varies between massifs, suggesting differential rotation before or during emplacement. Within North Arm Mountain, the olivine *a* axes are aligned approximately perpendicular to the sheeted dikes in both the ultramafic tectonites and the overlying gabbroic tectonites. In Blow Me Down Mountain, the olivine *a* axes in the gabbros are perpendicular to the dikes, but they are parallel to them in the ultramafic rocks. It is concluded that the ultramafic rocks on Blow Me Down Mountain were rotated 90° during emplacement or that local decoupling and rotation occurred between the crust and upper mantle prior to emplacement. Within the Lewis Hills, the olivine fabrics rotate and weaken near the shear zone in the center of the massif. A second deformation, perhaps associated with low-temperature plastic flow, appears to have obliterated the fabric patterns still observed in the ultramafic rocks to the east.

L'analyse de la pétrofabrique d'échantillons orientés de roches mafiques et ultramafiques prélevés sur six lignes transversales et représentatifs des quatre massifs du complexe ophiolitique de la Bay of Islands, Terre-Neuve, révèle que ces roches ultramafiques sont des tectonites avec des fabriques engendrées par un fluage plastique à température élevée sur les systèmes de glissement (010) [100] et (0*kl*) [100] de l'olivine. Il y a uniformité d'orientation de fabrique dans trois des quatre massifs, mais elle varie selon le massif, indiquant qu'il y a eu rotation avant et durant leur mise en place. L'axe *a* des grains d'olivine du mont North Arm est approximativement normal au complexe de filons verticaux dans les tectonites ultramafiques et aussi dans les tectonites gabbroïques sus-jacentes. L'axe *a* des grains d'olivine dans les gabbros du mont Blow Me Down est normal aux dykes, cependant il leur est parallèle dans les roches ultramafiques. Il apparaît donc que les roches ultramafiques du mont Blow Me Down aient subi une rotation de 90° durant leur mise en place ou qu'avant leur mise en place un découplage local accompagné d'une rotation se soit produit entre la croûte et le manteau supérieur. La fabrique de l'olivine dans les roches de Lewis Hills a subi une rotation et elle est atténuée près de la zone de cisaillement du centre du massif. Une deuxième déformation, possiblement associée à un fluage plastique de basse température, semble avoir masqué les motifs de fabrique, cependant encore visibles plus à l'est dans les roches ultramafiques.

[Traduit par le journal]

Can. J. Earth Sci. **22**, 1757–1766 (1985)

Introduction

Although geochemical and petrologic evidence amassed over the past 15 years has led to wide acceptance of the hypothesis that ophiolites represent fragments of oceanic crust and upper mantle emplaced on land (e.g., Coleman 1977), it is only recently that quantitative geophysical data have allowed a comparison of the ophiolites and the ocean crust in terms common to both. In particular, laboratory studies of the seismic velocities of ophiolite samples measured under conditions appropriate to the oceanic basement have demonstrated a remarkable similarity between the seismic velocity structure of the ophiolites and that of the ocean crust. For example, the studies of Peterson *et al.* (1974) and Christensen (1978) have shown a broad agreement between this structure and the early three-layered velocity models of the oceanic crust proposed by Raitt (1963), whereas more detailed studies based on numerous samples collected from known levels along traverses in both the Bay of Islands and Oman ophiolite complexes (Salisbury and Christensen 1978; Christensen and Smewing 1981; Christensen and Salisbury 1982) have demonstrated close agreement with more recent multilayered models deduced from data collected using continuous shooting techniques (e.g., Sutton *et al.* 1971) and the detailed gradient models derived from inversion and synthetic seismogram analysis (e.g., Spudich and Orcutt 1980; Kempner and Gettrust 1982*a*,*b*).

With the discovery by Hess (1964) of seismic anisotropy in the oceanic upper mantle from an analysis of refraction data obtained by Raitt (1963) near the Mendocino Fracture Zone and by Shor and Pollard (1964) off Hawaii and its subsequent observation throughout large areas in the Pacific Ocean (e.g., Morris *et al.* 1969), it has become apparent that anisotropy is one of the most diagnostic geophysical features of the oceanic upper mantle. From the refraction studies conducted to date, the anisotropy appears to vary from a maximum of 0.3 to 0.7 km/s and is aligned with the direction of maximum compressional wave velocity parallel or subparallel to the spreading direction inferred from magnetic anomaly patterns. As suggested by Birch (1961) and subsequently confirmed in detailed petrofabric and velocity studies of ultramafic rocks at elevated pressures (e.g., Christensen 1966; Christensen and Ramananantoandro 1971), such anisotropy can be readily explained in terms of the preferred crystallographic orientation of olivine, since single crystal olivine is strongly anisotropic,

[1]Present address: Centre for Marine Geology, Dalhousie University, Halifax, N.S., Canada B3H 3J5.

with compressional wave velocities of 9.87, 7.73, and 8.65 km/s in the *a*, *b*, and *c* directions, respectively (Verma 1960).

For the past several years, we have conducted an extensive sampling program throughout the ultramafic rocks of the Bay of Islands ophiolite complex in western Newfoundland in order to determine whether preferred mineral orientation and seismic anisotropy are present and of sufficiently regional extent to be observed over refraction paths of the length employed at sea to observe mantle anisotropy (>20 km). The Bay of Islands Complex was chosen for this study because (1) it is one of the few complexes in the world large and complete enough to allow such a test, (2) the presence of well developed sheeted dikes provides a structural reference frame within which the fabrics can be oriented with respect to the spreading direction, (3) the ultramafic rocks in the complex are well exposed, and (4) extensive mapping indicates that the complex is relatively uncomplicated by faulting (Smith 1958; Williams 1973) and has not been affected by regional metamorphism (Williams and Malpas 1972; Casey *et al.* 1981).

Christensen and Salisbury (1979) presented olivine petrofabrics for 17 ultramafic tectonites and gabbros from North Arm Mountain and Table Mountain (Fig. 1) and demonstrated that (1) the ultramafic rocks in both massifs display a strong *a* axis concentration subparallel to the plane of the Mohorovičić discontinuity and either a $b-c$ girdle or orthogonal *b* and *c* axis concentrations perpendicular to *a*; (2) the fabrics are remarkably uniform throughout each massif but are rotated with respect to each other by as much as 40°; (3) at least in North Arm Mountain, where the fabrics could be oriented with respect to the sheeted dikes, the *a* axes lie parallel to the spreading direction, and the compressional wave velocity anisotropy is consistent in direction and magnitude with that observed in the oceanic mantle; and (4) the ultramafic rocks within North Arm Mountain and Table Mountain are completely tectonized. Finally, and somewhat to our surprise, we observed that the basal olivine gabbros immediately overlying the ultramafic rocks are also tectonized and display the same olivine fabric as the underlying ultramafic rocks. These observations are in agreement with the conclusion of Nicolas and Prinzhofer (1983) that the uppermost ultramafic rocks of many ophiolites represent highly depleted tectonites of residual rather than magmatic cumulate origin.

In this paper, we present new olivine petrofabric data for 25 ultramafic and mafic samples from Blow Me Down Mountain and the Lewis Hills, three new petrofabrics from the western ultramafic limb of North Arm Mountain, and composite fabric diagrams for all four massifs. With these data and a knowledge of the elastic constants of olivine and their pressure derivatives (Verma 1960; Kumazawa and Anderson 1969), it is possible to compute the compressional and shear wave velocity as a function of direction for each sample and then compute composite velocity diagrams for each massif. From a comparison of such diagrams for all four massifs, it can be demonstrated that the seismic anisotropy observed in the Bay of Islands Complex is consistent in magnitude, direction, and scale with that observed in the oceanic upper mantle and is similar to the anisotropy observed in many ultramafic tectonites believed to have originated in the upper mantle (Peselnick and Nicolas 1978; Christensen 1984). In addition, and of prime importance, the new fabric data also provide previously unrecognized information on the structure of the Bay of Islands Complex and a model for upper mantle seismic anisotropy.

Olivine fabrics

The Bay of Islands Complex (Fig. 1) consists of four klippen of late Cambrian oceanic crust thrust over clastic sediments and carbonate platform deposits of early Cambrian to middle Ordovician age (Williams 1971; Jacobsen and Wasserberg 1979). Although the northernmost massif, Table Mountain, only displays a thin section of gabbro overlying ultramafic tectonites, the North Arm Mountain and Blow Me Down massifs appear to be nearly complete, with pillow basalts and sheeted dikes overlain by parallochthonous clastic marine sediments at the top of the section, gabbros at intermediate levels, and ultramafic tectonites at the base (Williams 1971, 1973; Casey and Kidd 1981). The southernmost massif, the Lewis Hills, is more complex, with a thin unit of gabbro, dunite, and peridotite on the east, a unit composed of metagabbro, metadiorite, and east–west-trending sheeted dikes on the west, and a 3–4 km wide, north–south-trending shear zone separating the two (Karson 1982). The shear zone has been interpreted as an oceanic transform fault and may once have been continuous with the Little Port Assemblage extending to the north-northeast along the coast (Karson and Dewey 1978).

In plan view, the crustal section of the Blow Me Down Massif appears to be exposed in a syncline with an attenuated northwest limb. As on North Arm Mountain, a well developed, subvertical sheeted dike complex striking 45° to the northwest provides an important structural reference frame.

As can be seen in Fig. 1, we examined the olivine fabrics in 17 field-oriented samples from Blow Me Down Mountain. Thirteen of the samples were ultramafic rocks collected along two parallel but widely separated traverses extending down section from the crust–mantle boundary into the ultramafic rocks. The remaining four samples consisted of one ultramafic rock (sample 214A) collected on the southwest limb of the massif as a structural check, two gabbros (39A and 58) collected near the base of the gabbro unit, and a plagioclase peridotite (28) collected near the top of the ultramafic section.

In addition to these samples, we collected eight field-oriented ultramafic samples at widely dispersed locations in the eastern half of the more complex terrain mapped by Smith (1958), Williams (1973), and Karson (1982) in the Lewis Hills in order to check for lateral heterogeneity and to compare the olivine fabric with that of the other massifs. Since dikes are not present in this portion of the Lewis Hills, however, the samples can only be oriented with respect to the trend of the shear zone and the sheeted dikes to the west. Finally, we collected three new ultramafic rock samples (201C, 202A, and 203C) from the west limb of North Arm Mountain for structural interpretation purposes. As in North Arm Mountain and Table Mountain, the ultramafic rocks from Blow Me Down Mountain and the Lewis Hills are strongly serpentinized. Since serpentinization appears to take place statically either during or after emplacement (e.g., Wenner and Taylor 1973; Margaritz and Taylor 1974), the original fabric may be reconstructed using universal stage techniques if sufficient relict olivine grains are present in each sample. Figures 2, 3, and 4 show the results of these measurements for the samples collected and discussed above from Blow Me Down Mountain, the Lewis Hills, and North Arm Mountain, respectively. Each fabric diagram shows orientation data for 100 grains using the contouring method described by Kamb (1959). The fabrics are presented relative to a horizontal reference frame (i.e., plan view) with North marked on each diagram. Composite fabric diagrams using the same reference frame are shown for each massif in Fig. 5.

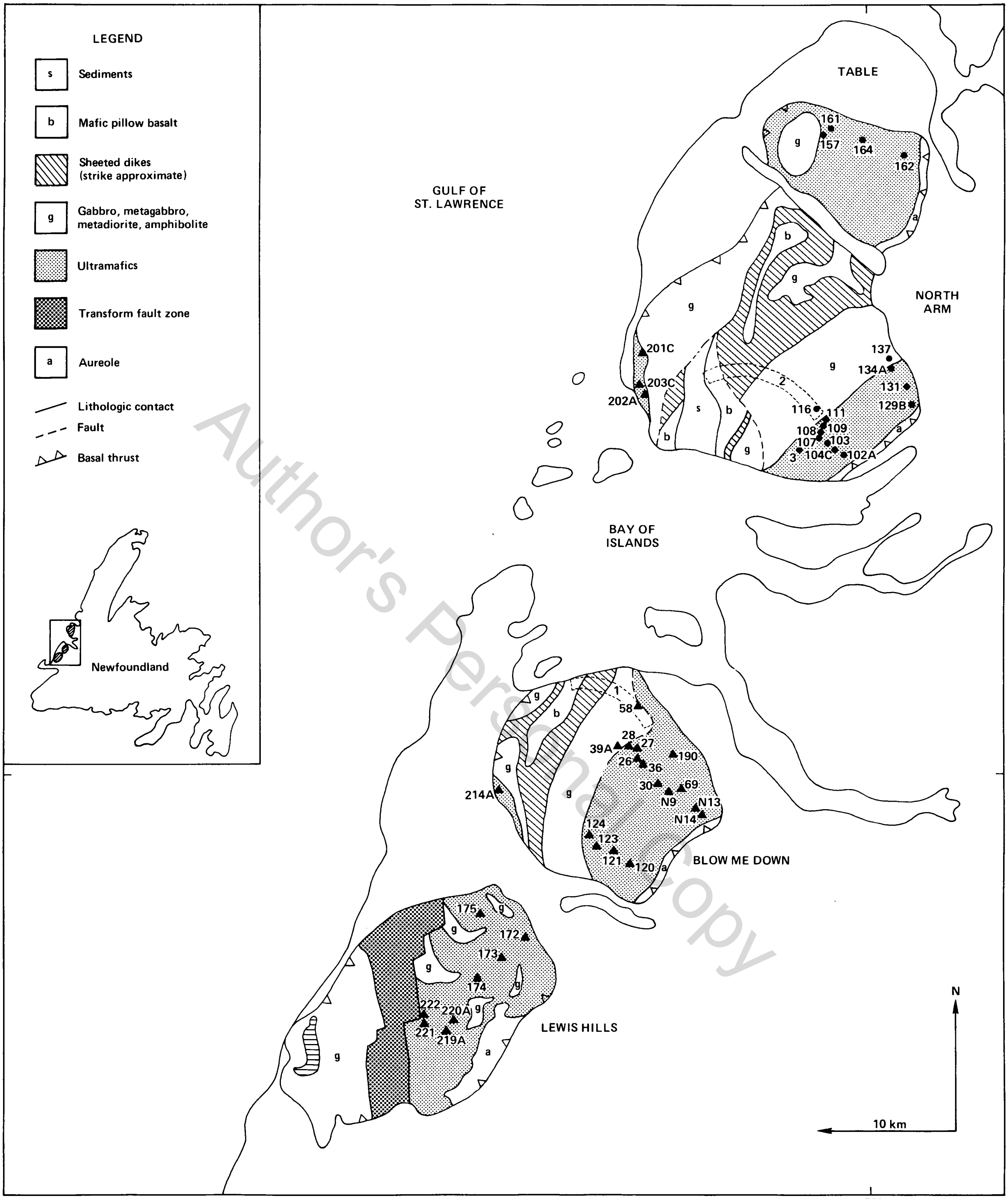

FIG. 1. Location of samples used for petrofabric studies from the Bay of Islands ophiolite complex: ▲, this study; ●, Christensen and Salisbury (1979). Dashed lines show locations of crustal seismic velocity profiles discussed for (1) Blow Me Down Mountain (Salisbury and Christensen 1978) and (2) North Arm Mountain (Christensen and Salisbury 1982). Simplified geology after Williams (1973), Casey and Kidd (1981), and Karson (1982).

The individual petrofabrics shown in Fig. 2 and the composite fabric shown in Fig. 5 for the Blow Me Down ultramafic rocks display a remarkably uniform orientation throughout most of the section: the olivine *a* axes form well defined maxima that strike northwest–southeast and dip about 30° to the northwest, the *b* axes dip about 70° to the southeast, and the *c* axes lie subhorizontally and strike northeast–southwest. Toward the base of the section (samples N13 and N14) and inter-

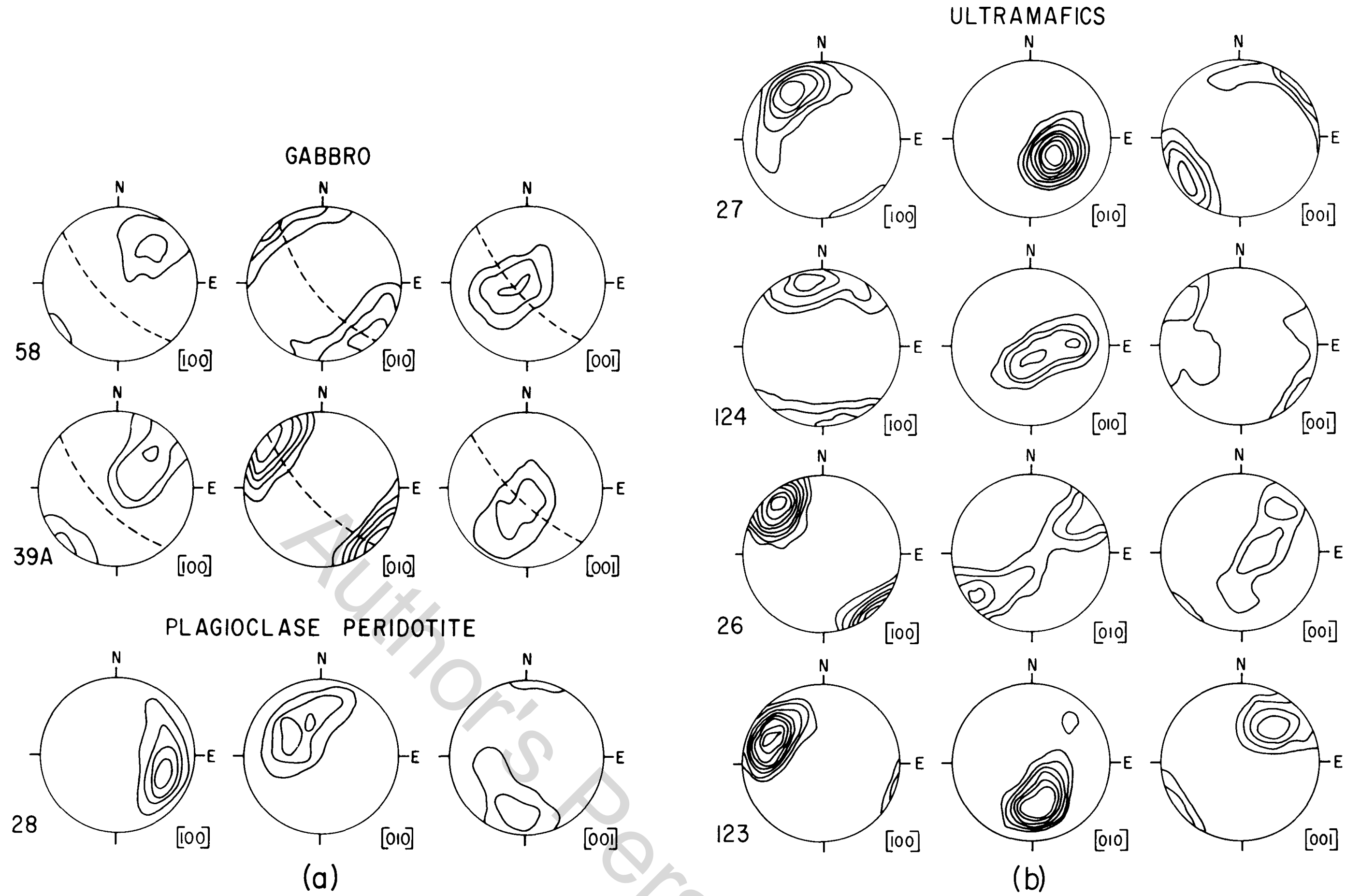

FIG. 2. Equal-area, lower hemisphere projections of [100], [010], and [001] axes of olivine plotted as Kamb diagrams for samples from the southeast limb of Blow Me Down Mountain, in order of increasing depth. Samples 120, 121, 123, and 124 are from the southern traverse shown in Fig. 1; the remaining samples are from the northeast traverse. Sample 214A from the southwest limb of the massif is also shown for comparison. Dashed great circle in gabbros shows mean orientation of sheeted dikes. Projection contoured in 2σ intervals, with the lowest contour $= 4\sigma$; $\sigma = 2.75$; $E = 3\sigma$; counting area $A = 0.083$; $N = 100$ for each sample.

mittently at higher levels (samples 26 and 190), the symmetry changes, with the *a* axes dipping 30° to northwest, as before, but with the *b* and *c* axes now forming weak girdles about the *a* axes. Since the *a* axis orientation remains constant throughout the section and parallel to the spinel lineations reported in the Blow Me Down ultramafic rocks (Girardeau 1979), the two fabrics appear closely related.

Since the sheeted dikes on Blow Me Down Mountain are subvertical and strike to the northwest, we had anticipated that the olivine *a* axes in the ultramafic tectonites would be aligned perpendicular to the dikes and strike to the northeast, subparallel to the plane of the Mohorovičić discontinuity, as observed on North Arm Mountain (Christensen and Salisbury 1979). As can be seen in Figs. 2 and 5, however, the *a* axes lie approximately in the plane of the dikes. On the other hand, the olivine in the gabbros immediately above the gabbro–ultramafic contact (samples 58 and 39A) displays a strong tectonite fabric in which the *a* axes are aligned perpendicular to the dikes and the *b* and *c* axes form maxima in the plane of the dikes, whereas the ultramafic rock sampled along the contact (sample 28) shows a fabric that is inconsistent with those observed in either the gabbros or the underlying ultramafic tectonites.

As can be seen in Fig. 5, the composite olivine fabric in the samples from the Lewis Hills is similar to that observed on Blow Me Down Mountain: the *a* axis concentration strikes northwest–southeast and lies subparallel to the plane of the Mohorovičić discontinuity, which in this instance is subhorizontal. If the individual fabric diagrams in Fig. 3 are examined, however, it is clear that the fabrics change in intensity and direction in the center of the massif. The *a* axis concentration strikes almost due north in the sample taken farthest to the east (172) but shifts to the northwest toward the center of the massif (220A), with two of the intermediate samples (174 and 175) actually displaying bimodal axis concentrations. Interestingly, the fabrics in the ultramafic rocks sampled nearest the proposed transform fault (samples 221 and 222) are only weakly developed (Figs. 1, 3).

Finally, the fabrics shown in Fig. 4 for the west limb of North Arm Mountain (samples 203C, 201C, and 202A) show the same symmetry as that found on the southeast limb (Christensen and Salisbury 1979) but with a different orientation. The olivine *a* axes again lie approximately in the plane of the gabbro–peridotite contact, but this contact now strikes north-northwest and is subvertical (Fig. 1), and the *b* axes strike northeast. Since this orientation pattern and that found in the southeast limb (Fig. 5) are consistent with exposure in a syncline, we conclude that the entire section has been folded. It should be noted, incidentally, that the situation is quite different on Blow Me Down Mountain. Although the outcrop

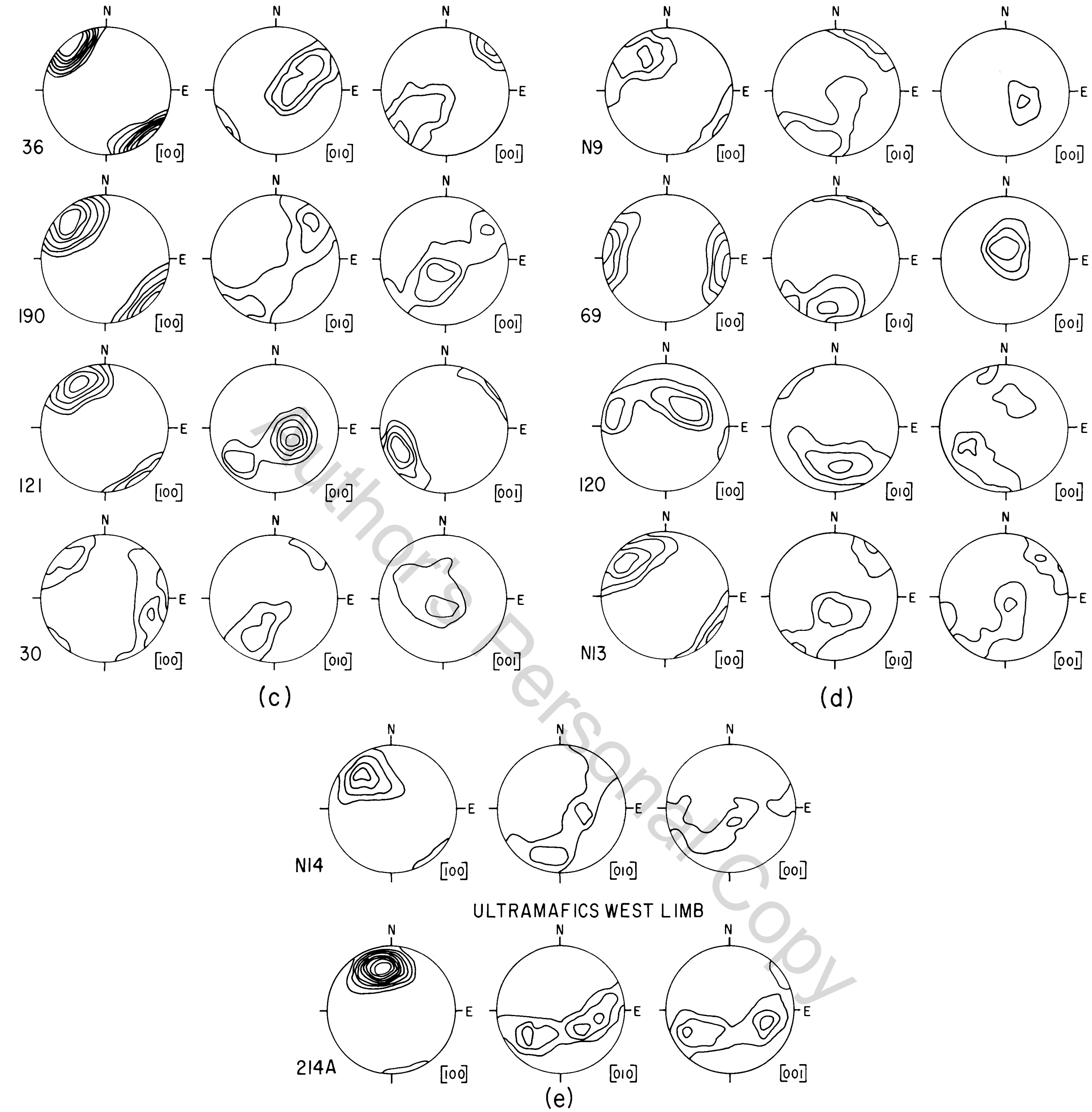

FIG. 2. (*Concluded.*)

pattern again suggests exposure in a syncline, the olivine fabric in sample 214A (Fig. 2), collected along the southwest limb of Blow Me Down Mountain, is similar to that observed in the ultramafic rocks from the southeast limb.

Calculated velocities

From the universal stage data used to construct the fabric diagrams of Figs. 2–4, it is possible to compute the compressional and shear-wave velocity as a function of direction using the technique described by Crosson and Lin (1971), the elastic constants of olivine and their derivatives with respect to pressure (Kumazawa and Anderson 1969), the pressure appropriate for each sample, and the density of olivine. If the data from more than one sample are used in such a computation, it is possible to derive a composite velocity diagram analogous to the composite fabric diagrams shown in Fig. 5. The compressional wave velocity diagrams shown in Fig. 6, which were computed by this means for the same samples, present the average mantle velocity as a function of direction for each massif in its present orientation.

In any anisotropic medium, two orthogonally polarized shear waves travelling at different velocities will generally be observed for any given propagation direction. The corresponding maximum and minimum shear wave velocities, $V_{s\,max}$ and

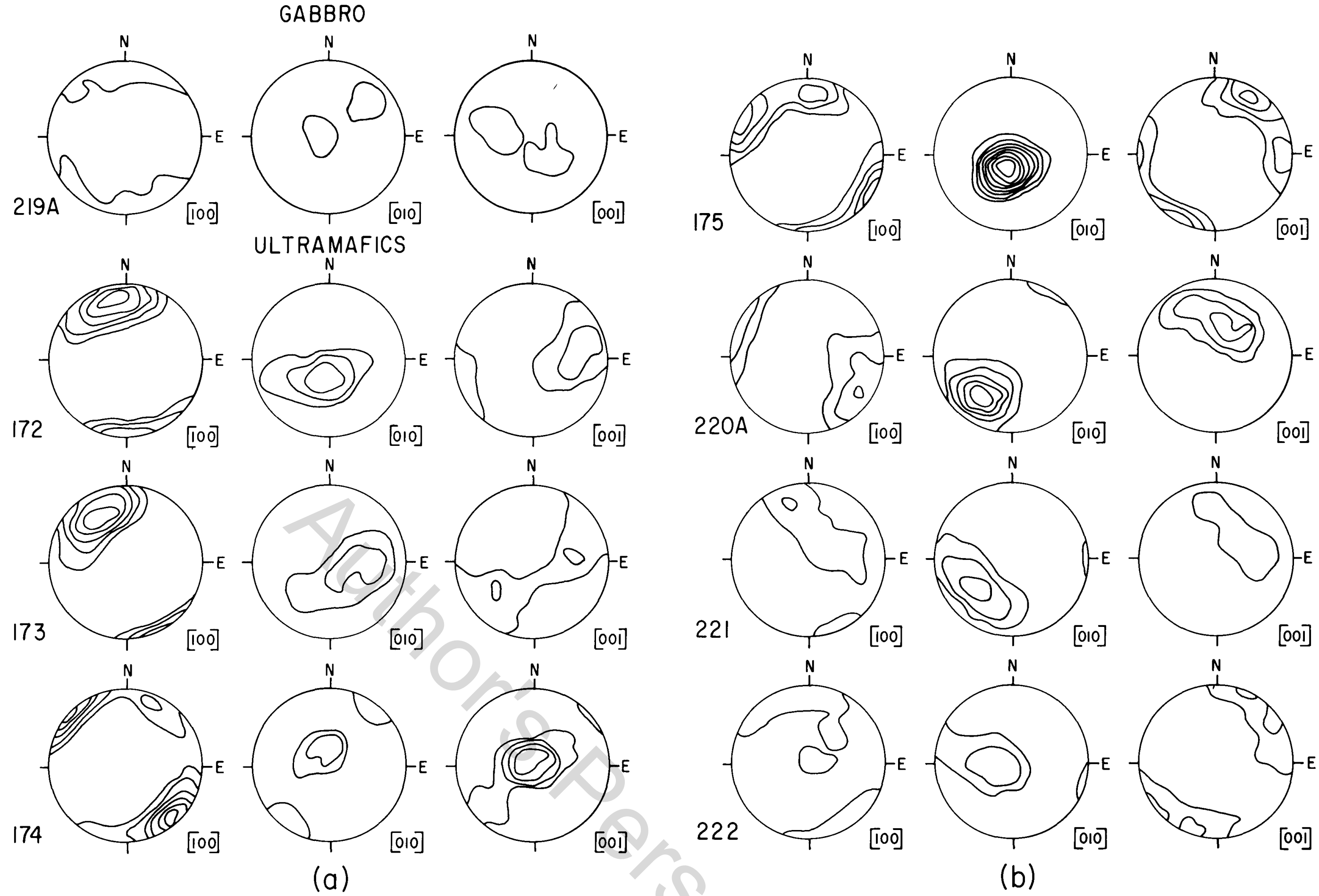

FIG. 3. Equal-area, lower hemisphere projections of [100], [010], and [001] axes of olivine plotted as Kamb diagrams for samples from the Lewis Hills. The ultramafic samples are plotted in order of increasing proximity to the north–south shear zone in the center of the massif. Projection contoured in 2σ intervals, with lowest contour = 4σ; $\sigma = 2.75$; $E = 3\sigma$; counting area $A = 0.083$; $N = 100$ for each sample.

$V_{s\,min}$, computed for each propagation direction using the Cristoffel equations, are also shown in Fig. 6 along with the difference in velocity, ΔV_s.

As can be seen in Fig. 6, the ultramafic sections in all four massifs display a well developed compressional wave anisotropy pattern in which the velocity ranges from a maximum of more than 8.7 km/s to a minimum of less than 8.2 km/s. Although the mean velocity, 8.5 km/s, is higher than the mean P_n velocity observed at sea (8.1 km/s), the difference is negligible when the effects of temperature, pyroxene content, and accessory minerals are taken into account (Christensen and Salisbury 1979; Christensen and Lundquist 1982). In North Arm Mountain, where the section studied is continuous, the fast direction is aligned subperpendicular to the plane of the sheeted dikes, and the compressional wave anisotropy in the plane of the Mohorovičić discontinuity is about 5%, in excellent agreement with both theory and observations at sea (Christensen and Salisbury 1979). The orientation of olivine in the ultramafic rocks on Blow Me Down Mountain, however, is at odds with both theory and the observations on North Arm: the fast direction is aligned parallel, rather than perpendicular, to the dikes.

Within the two remaining massifs, Table Mountain and the Lewis Hills, the compressional wave velocity diagrams are similar, but their orientation with respect to the spreading direction cannot be determined with certainty because the sheeted dikes have either been removed by erosion (Table Mountain) or, if present, are found in a separate fault block (Lewis Hills). Nonetheless, Fig. 1 suggests that the spreading direction can be determined approximately for the Lewis Hills if the shear zone is indeed a transform fault and the dikes in the western block have suffered no rotation. On the eastern edge of the Lewis Hills, the fast direction, which coincides with the olivine *a* axis maximum, lies in the plane of the Mohorovičić discontinuity and is aligned subparallel to the spreading direction defined both by the transform fault and the dikes. As the fault is approached, however, the fast direction gradually rotates until it is inclined 45° to the spreading direction, and there is a significant decrease in the magnitude of the compressional wave anisotropy, as shown by the relatively weak fabrics of samples 221 and 222 (Fig. 3*b*).

Although all four massifs display pronounced compressional wave anisotropy, the shear wave anisotropy patterns are less straightforward. As can be seen in Fig. 6, the faster of the two shear waves ($V_{s\,max}$) propagating through the ultramafic units travels at about the same velocity in all directions. On North Arm Mountain, where the section is continuous, the slower wave ($V_{s\,min}$) displays a weakly developed anisotropy pattern in which the fast direction is aligned perpendicular to the sheeted dikes, causing the shear wave splitting, ΔV_s, to be greatest parallel to the dikes.

Implications and conclusions

During the course of this and our earlier studies in the Bay

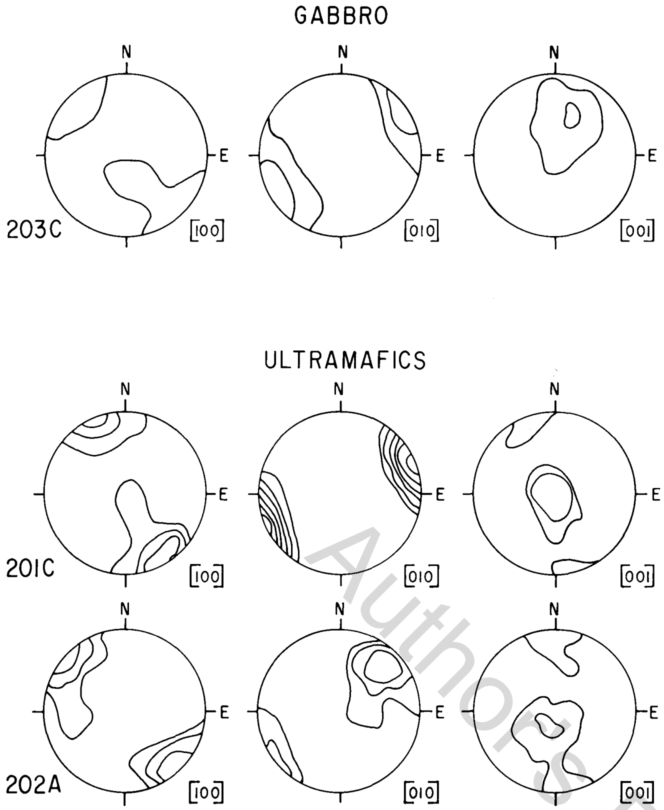

FIG. 4. Equal-area, lower hemisphere projections of [100], [010], and [001] axes of olivine plotted as Kamb diagrams for samples from the west limb of North Arm Mountain. Projection contoured in 2σ intervals, with the lowest contour = 4σ; $\sigma = 2.75$; $E = 3\sigma$; counting area $A = 0.083$; $N = 100$ for each sample.

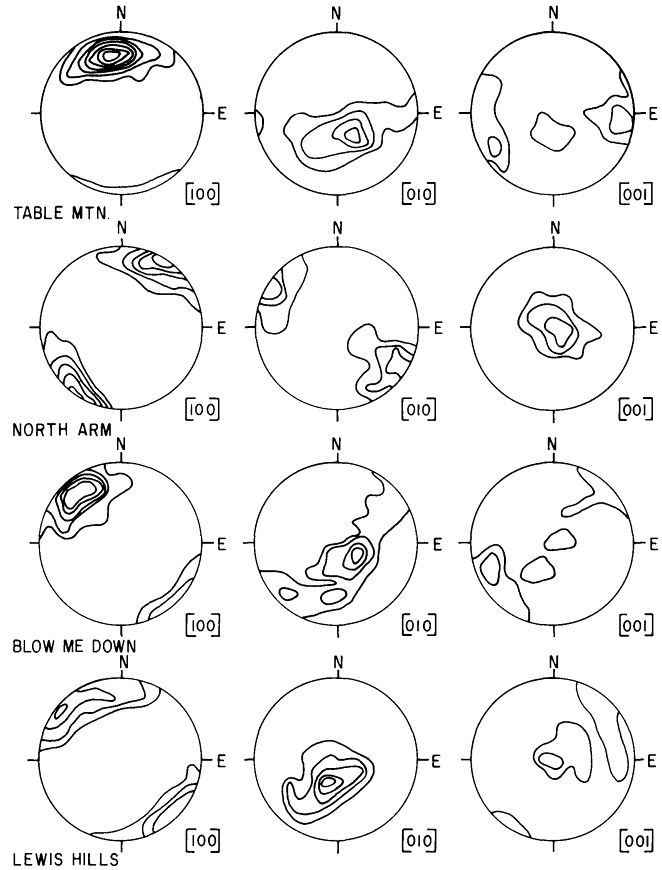

FIG. 5. Composite olivine fabric diagrams for ultramafic and gabbroic samples from each massif of the Bay of Islands ophiolite complex. Diagrams represent equal-area, lower hemisphere Kamb plots of [100], [010], and [001] axes of olivine. Projection contoured in 2σ intervals, with lowest contour = 4σ; $\sigma = 2.75$; $E = 3\sigma$; counting area $A = 0.083$; $N = 300$ (three samples, excluding 157) for Table Mountain, 1200 (12 samples, excluding 116, 203C, 201C, and 202A) for North Arm Mountain, 1300 (13 samples, excluding 58, 39A, 28, and 214A) for Blow Me Down Mountain, and 500 (five samples, excluding 219A, 221, and 222) for the Lewis Hills. Diagrams for Table Mountain and North Arm Mountain based on data presented by Christensen and Salisbury (1979).

of Islands ophiolite complex (Christensen and Salisbury 1979), we have determined the orientation of 4500 olivine grains in 45 field-oriented samples, including 37 ultramafic tectonites, two plagioclase peridotites, and six olivine gabbros collected from six widely spaced traverses representing all four massifs in the complex. From the results of these studies, it is possible to reach a number of important conclusions concerning both the Bay of Islands ophiolite complex and the ocean crust and upper mantle as a whole:

(1) First, except in the immediate vicinity of the shear zone in the Lewis Hills, the ultramafic rocks and basal gabbros throughout the Bay of Islands Complex display strong tectonite fabrics with orthogonal olivine *a*, *b*, and *c* axis concentrations. In addition, fabrics with *b* and *c* girdles about a strong *a* maximum are common. When these fabrics are intermixed, the *a* axes are parallel, suggesting that the two fabrics are closely related. This preferred orientation is consistent with high-temperature plastic flow with slip on the (010) [100] and (0*kl*) [100] olivine slip systems (Raleigh 1968).

In the vicinity of the shear zone in the Lewis Hills, however, the olivine fabrics are anomalous. If the shear zone were a transform fault, the olivine *a* axes should be strongly aligned parallel to the fault (A. Nicolas, personal communication, 1984) and the *b* axes should be aligned perpendicular. Instead, the olivine *a* axis concentrations are extremely weak and the *a* and *b* axis maxima trend obliquely to the fault. A second deformation appears to have obliterated the fabric patterns still observed in the ultramafic rocks to the east. We tentatively ascribe the origin of these fabrics to activation of the olivine low-temperature slip system (110) [001] observed near contact aureoles (e.g., Boudier and Coleman 1981).

(2) The olivine *a* axes in the basal gabbros lie subparallel to the plane of the Mohorovičić discontinuity throughout the Bay of Islands Complex, and where sheeted dikes are present, as on North Arm Mountain, Blow Me Down Mountain, and the Lewis Hills, the *a* axes are aligned perpendicular to the dikes. This indicates that the lowermost gabbros are tectonites. If the high-velocity basal layer of Sutton *et al.* (1971) corresponds to such gabbroic tectonites, it would presumably display lower velocities and thus be more difficult to detect parallel to the ridge.

(3) In the underlying ultramafic tectonites, however, the situation is much more complicated. The *a* axes always lie subparallel to the plane of the Mohorovičić discontinuity, as in the gabbros, and the ultramafic fabrics are strikingly uniform within each massif, but on Blow Me Down Mountain and at least locally in the Lewis Hills the ultramafic fabric is rotated with respect to that in the gabbros, suggesting a fault contact.

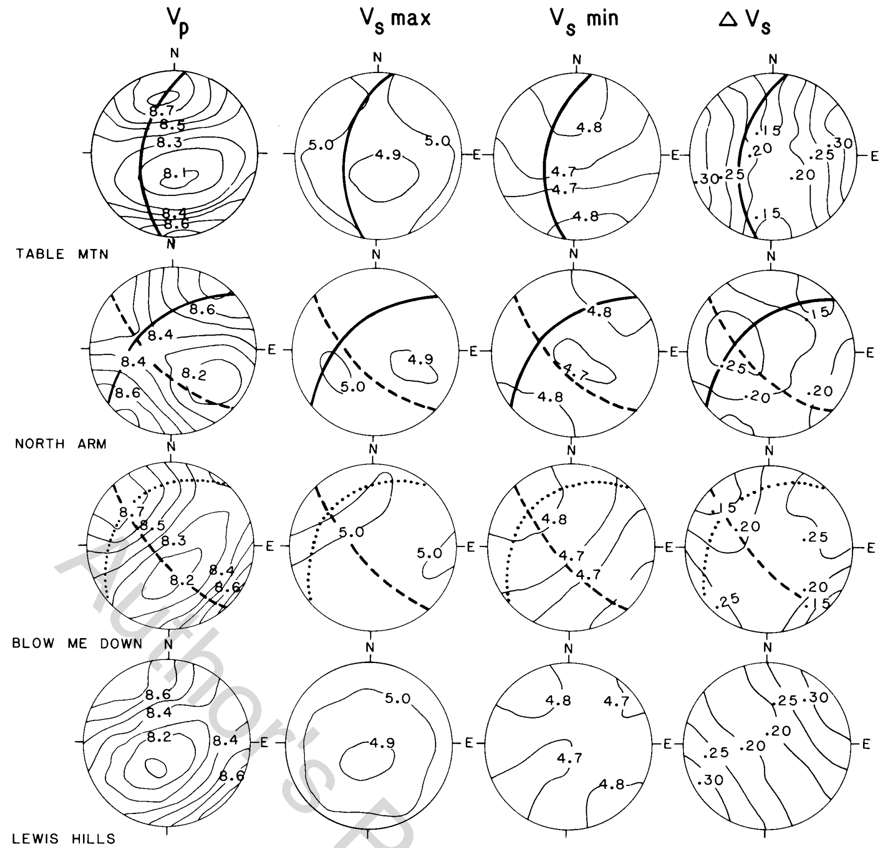

FIG. 6. Composite compressional wave (V_P) velocity diagrams based on fabrics shown in Fig. 5 for Table Mountain, North Arm Mountain, Blow Me Down Mountain, and the Lewis Hills. Also shown are composite projections for the maximum and minimum shear wave velocities, $V_{s\ max}$ and $V_{s\ min}$, in kilometres per second and the shear wave splitting, ΔV_s, in kilometres per second. Velocity projections contoured in 0.1 km/s intervals. Dashed great circles (North Arm Mountain and Blow Me Down Mountain) represent the attitude of the sheeted dikes, and solid great circles (Table Mountain and North Arm Mountain) represent the attitudes of the boundary between the gabbros and the ultramafic units. Dotted line (Blow Me Down Mountain) represents approximate attitude of proposed fault near mafic-ultramafic contact.

Where the gabbros and ultramafic rocks are structurally continuous, however, as on North Arm Mountain, the gabbroic and ultramafic fabrics are continuous.

Two explanations can be invoked to explain these fabrics. One possibility is that the ultramafic units originally had the same orientation as the gabbros but that faulting and rotation occurred between, and in some cases within, the four massifs during emplacement of the complex on land. Alternatively, the faulting and rotation could have occurred before emplacement, in which case the observed fabric patterns are oceanic in origin. Although we prefer the former interpretation because oceanic mantle anisotropy seems to require regional continuity of fabric, with the olivine *a* axes subparallel to spreading, and we feel that the fabric in both the gabbros and ultramafics in any one massif must originally have formed in a common stress field, we have no absolute grounds for deciding between the two. In either case, the implications are far reaching:

If the olivine *a* axes in the gabbros and ultramafic units were originally aligned perpendicular to the dikes and the dikes themselves were parallel, as in Fig. 7*a*, then the relative translation and rotation of the massifs during emplacement were comparatively simple (Fig. 7*b*), except in the case of Blow Me Down Mountain, which divided into two sections, the lower of which was rotated 90° with respect to the upper.

If the reconstruction shown in Fig. 7 is correct and the *a* axes were aligned subparallel to the spreading direction throughout the complex, then the compressional wave anisotropy was consistent in magnitude and direction with that observed in the oceanic upper mantle and was present on a scale comparable to the path lengths required to determine mantle velocities in marine refraction experiments (>20 km).

(4) Although the compressional wave anisotropy discussed above has been amply documented at sea, the shear wave patterns have not been observed. It is anticipated that the anisotropic behavior of shear waves in the oceanic upper mantle could be confirmed through observations with ocean bottom seismometers. Because of the relative inefficiency of P to SH energy conversion in seismic experiments at sea, however, it is probable that the more diagnostic shear wave splitting patterns shown in Fig. 6 can only be detected through the use of clamped, three-component borehole seismometers.

If the alternative interpretation is correct, namely that local decoupling and relative rotation of the oceanic crust and upper mantle occurred before emplacement on land, then locales must exist in the ocean basins where the olivine fabric is heterogeneous. Refraction studies suggest that the ridge crest is such an environment, since seismic anisotropy is rarely observed in young crust but appears to become pronounced with age (Whitmarsh 1971). If the Bay of Islands ophiolite complex was emplaced on land shortly after formation and thus reflects such an environment, then the samples examined here suggest that mantle fabrics in the vicinity of the ridge crest are only uniform

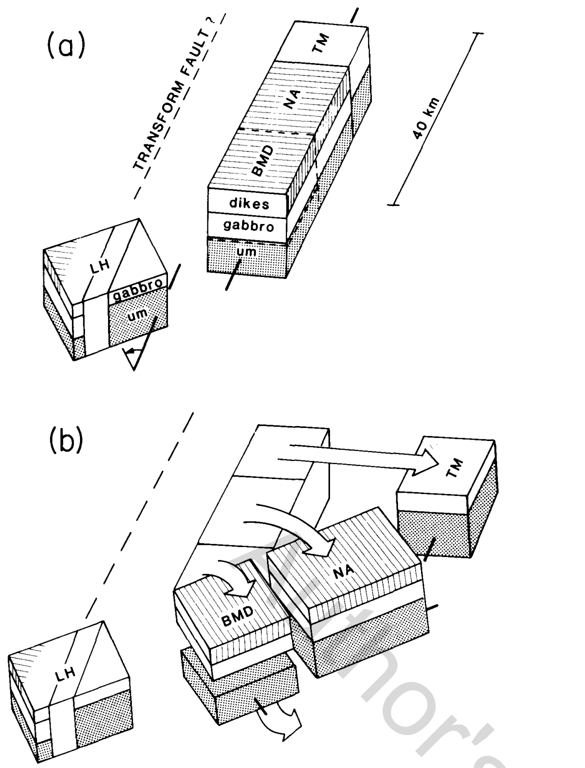

FIG. 7. Relative orientation of Lewis Hills (LH), Blow Me Down Mountain (BMD), North Arm Mountain (NA), and Table Mountain (TM) before (*a*) and after (*b*) emplacement on land. Parallel lines show dike orientation; spokes show orientation of *a* axes; arrows indicate directions of translation and rotation.

on a scale of up to 10 km and that mantle flow patterns in the upwelling zone are complex. This may explain why the fast direction, which is generally parallel to spreading, has been observed to deviate from it by as much as 18° (Keen and Barrett 1971). This also suggests that the oceanic crust may be locally and perhaps regionally decoupled from the mantle and that where this is the case the Mohorovičić discontinuity is marked by a décollement.

Acknowledgments

We wish to express our thanks to J. Willemin, J. Hull, S. Lundquist, and L. Slater for their help in the laboratory during the course of this study. We also wish to thank H. Williams for his advice in planning this investigation and for providing unpublished maps of the area and A. Nicolas and T. Calon for their helpful critiques of the manuscript. Financial support was provided by Office of Naval Research contract N-00014-80-C-0252.

BIRCH, F. 1961. The velocity of shear waves in rocks to 10 kilobars, 2. Journal of Geophysical Research, **66**, pp. 2199–2224.

BOUDIER, F., and COLEMAN, R. G. 1981. Cross section through peridotite in the Samail Ophiolite, southeastern Oman Mountains. Journal of Geophysical Research **86**, pp. 2573–2592.

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. Canadian Journal of Earth Sciences, **18**, pp. 1035–1050.

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 complex. *In* The sea. Vol. 7. *Edited by* C. Emiliani. John Wiley & Sons, New York, NY, pp. 305–338.

CHRISTENSEN, N. I. 1966. Elasticity of ultrabasic rocks. Journal of Geophysical Research, **71**, pp. 5921–5931.

——— 1978. Ophiolites, seismic velocities and oceanic crustal structure. Tectonophysics, **47**, pp. 131–157.

——— 1984. The magnitude, symmetry and origin of upper mantle anisotropy based on fabric analysis of ultramafic tectonites. Geophysical Journal of the Royal Astronomical Society, **76**, pp. 89–111.

CHRISTENSEN, N. I., and LUNDQUIST, S. M. 1982. Pyroxene orientation within the upper mantle. Geological Society of America Bulletin, **93**, pp. 279–288.

CHRISTENSEN, N. I., and RAMANANANTOANDRO, R. 1971. Elastic moduli and anisotropy of dunite to 10 kilobars. Journal of Geophysical Research, **76**, pp. 4003–4010.

CHRISTENSEN, N. I., and SALISBURY, M. H. 1979. Seismic anisotropy in the oceanic upper mantle: evidence from the Bay of Islands ophiolite complex. Journal of Geophysical Research, **84**, pp. 4601–4610.

——— 1982. Lateral heterogeneity in the seismic structure of the ocean crust inferred from velocity studies in the Bay of Islands Ophiolite, Newfoundland, Geophysical Journal of the Royal Astronomical Society, **68**, pp. 675–688.

CHRISTENSEN, N. I., and SMEWING, J. A. 1981. Geology and seismic structure of the northern section of the Oman Ophiolite. Journal of Geophysical Research, **86**, pp. 2545–2555.

COLEMAN, R. G. 1977. Ophiolites. Springer-Verlag, New York, NY, 230 p.

CROSSON, R. S., and LIN, J. W. 1971. Voigt and Reuss prediction of anisotropic elasticity of dunite. Journal of Geophysical Research, **76**, pp. 570–578.

GIRARDEAU, J. 1979. Structure des ophiolites de l'ouest de Terre-Neuve et modèle de croûte océanique. Ph.D. thesis, University of Nantes, Nantes, France.

HESS, H. H. 1964. Seismic anisotropy of the uppermost mantle under oceans. Nature (London), **203**, pp. 629–631.

JACOBSEN, 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. Journal of Geophysical Research, **84**, pp. 7429–7445.

KAMB, W. B. 1959. Ice petrofabric observations from the Blue Glacier, Washington, in relation to theory and experiment. Journal of Geophysical Research, **64**, pp. 1891–1909.

KARSON, J. A. 1982. Reconstructed seismic velocity structure of the Lewis Hills Massif and implications for oceanic fracture zones. Journal of Geophysical Research, **87**, pp. 961–978.

KARSON, J. A., and DEWEY, J. F. 1978. Coastal Complex, western Newfoundland: an early Ordovician oceanic fracture zone. Geological Society of America Bulletin, **89**, pp. 1037–1049.

KEEN, C. E., and BARRETT, D. L. 1971. A measurement of seismic anisotropy in the northeast Pacific. Canadian Journal of Earth Sciences, **8**, pp. 1056–1064.

KEMPNER, W. C., and GETTRUST, J. F. 1982*a*. Ophiolites, synthetic seismograms, and oceanic crustal structure, 1. Comparison of ocean bottom seismometer data and synthetic seismograms for the Bay of Islands Ophiolite. Journal of Geophysical Research, **87**, pp. 8447–8462.

——— 1982*b*. Ophiolites, synthetic seismograms, and oceanic crustal structure, 2. A comparison of synthetic seismograms of the Samail Ophiolite, Oman, and the Rose refraction data from the East Pacific Rise. Journal of Geophysical Research, **87**, pp. 8463–8476.

KUMAZAWA, M., and ANDERSON, O. L. 1969. Elastic moduli, pressure derivatives and temperature derivatives of single crystal olivine and single crystal forsterite. Journal of Geophysical Research, **74**, pp. 5961–5972.

MARGARITZ, M., and TAYLOR, H. 1974. Oxygen and hydrogen isotope studies of serpentinization in the Troodos ophiolite complex.

Earth and Planetary Science Letters, **23**, pp. 8–14.

MORRIS, G. B., RAITT, R. W., and SHOR, G. G. 1969. Velocity anisotropy and delay-time maps of the mantle near Hawaii. Journal of Geophysical Research, **74**, pp. 4301–4316.

NICOLAS, A., and PRINZHOFER, A. 1983. Cumulative or residual origin for the transition zone in ophiolites: structural evidence. Journal of Petrology, **24**, Part 2, pp. 188–206.

PESELNICK, L., and NICOLAS, A. 1978. Seismic anisotropy in an ophiolite peridotite: application to oceanic upper mantle. Journal of Geophysical Research, **83**, pp. 1227–1235.

PETERSON, J. J., FOX, P. J., and SCHREIBER, E. 1974. Newfoundland ophiolites and the geology of the oceanic layer. Nature (London), **247**, pp. 194–196.

RAITT, R. W. 1963. The crustal rocks. *In* The sea. Vol. 3. *Edited by* M. N. Hill. John Wiley & Sons, New York, NY, pp. 85–102.

RALEIGH, C. B. 1968. Mechanism of plastic deformation of olivine. Journal of Geophysical Research, **73**, pp. 5391–5406.

SALISBURY, M. H., and CHRISTENSEN, N. I. 1978. The seismic velocity structure of a traverse through the Bay of Islands ophiolite complex, Newfoundland, an exposure of oceanic crust and upper mantle. Journal of Geophysical Research, **83**, pp. 805–817.

SHOR, G. G., JR., and POLLARD, D. D. 1964. Mohole site selection studies north of Maui. Journal of Geophysical Research, **69**, pp. 1627–1637.

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

SPUDICH, P., and ORCUTT, J. 1980. A new look at the seismic velocity structure of the oceanic crust. Reviews of Geophysics and Space Physics, **18**, pp. 627–645.

SUTTON, G. H., MAYNARD, G. L., and HUSSONG, D. M. 1971. Widespread occurrence of a high-velocity basal layer in the Pacific crust found with repetitive sources and sonobuoys. *In* The structure and physical properties of the Earth's crust. Geophysical Monograph Series, Vol. 14. *Edited by* J. G. Heacock. American Geophysical Union, Washington, DC, pp. 193–209.

VERMA, R. K. 1960. Elasticity of some high density crystals. Journal of Geophysical Research, **65**, pp. 757–766.

WENNER, D. B., and TAYLOR, H. P. 1973. Oxygen and hydrogen isotope studies of the serpentinization of ultramafic rocks in oceanic and continental ophiolite complexes. American Journal of Science, **273**, pp. 207–239.

WHITMARSH, R. B. 1971. Seismic anisotropy of the uppermost mantle absent beneath the east flank of the Reykjanes Ridge. Bulletin of the Seismological Society of America, **61**, pp. 1351–1368.

WILLIAMS, H. 1971. Mafic–ultramafic complexes in western Newfoundland Appalachians and the evidence for transportation: review and interim report. Proceedings of the Geological Association of Canada, **24**(1), pp. 9–25.

——— 1973. The Bay of Islands map-area, Newfoundland. Geological Survey of Canada, Paper 72–34, pp. 1–7.

WILLIAMS, H., and MALPAS, J. 1972. Sheeted dikes and brecciated dike rocks within transported igneous complexes, Bay of Islands, western Newfoundland. Canadian Journal of Earth Sciences, **9**, pp. 1216–1229.