Structure and origin of the Dun Mountain ultramafic massif, New Zealand

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ABSTRACT

Dun Mountain, the type locality of dunite, forms part of a major belt of predominantly mafic and ultramafic rocks in South Island, New Zealand. The core of the mountain consists of unserpentinized dunite and harzburgite tectonite. Foliations in the ultramafic rocks strike approximately northeast-southwest, parallel to the elongation of the crestal plateau. Lineations are horizontal and northeast-southwest. Texture is usually porphyroclastic, with olivine elongated parallel to lineations. Petrofabric analyses show strong preferred orientations of olivine *a* crystallographic axes subparallel to foliations and lineations. Shear senses within the ultramafic are dextral, indicating that the northern portion of Dun Mountain has been displaced to the east relative to the southern portion. Undulatory extinction of olivine, resulting from kinking and associated slip on (010) [100] and {0k1} [100] slip systems, is interpreted as originating within the upper mantle beneath oceanic crust that formed at a spreading ridge or in a marginal basin. Seismic anisotropy of the Dun Mountain ultramafic is similar to observed anisotropy in the upper oceanic mantle.

INTRODUCTION

Dun Mountain, located ~10 km southeast of Nelson on South Island, New Zealand, is the type locality of dunite. The rock was originally named by von Hochstetter (1864) after the dun-brown–colored mountain, which in places is largely devoid of vegetation. The fresh rock is light olive green in color, whereas a thin weathering rind common on the rock exposures has a characteristic reddish-brown color. This, as well as the presence of tussock, a tan grass that covers the shallower slopes, is responsible for the dun color of the mountain, which stands out in direct contrast to the dark green bush and trees of the surrounding hills.

Early studies proposed an igneous origin for the dunite. McKay (1879) suggested that the ultramafic rocks originated as submarine lava flows, whereas Park (1887) and Benson (1926) favored an intrusive origin. Turner (1942) concluded, on the basis of petrofabric studies, that the olivine from Dun Mountain did not originate from crystal settling in a large magma chamber. Instead, he proposed an origin as an inclined sill injected along a major fault zone. Turner (1942) presented evidence for postemplacement deformation of the ultramafic, as did Battey (1960), who suggested that deformation features and preferred olivine orientation in Dun Mountain are related to regional folding. Lauder (1965), on the other hand, interpreted the olivine orientation obtained by petrofabric analyses as originating from crystal settling within a volcanic pipe. In support of this origin, he proposed that Dun Mountain is composed of concentric zones of dunite and harzburgite a few hundred metres in width formed by deposition of crystals on the walls of the pipe during successive pulses of magma injection. Challis (1965) also considered the Dun Mountain ultramafic to be of igneous origin but suggested that it formed as a differentiate within a deep-level magma chamber underlying Permian volcanoes.

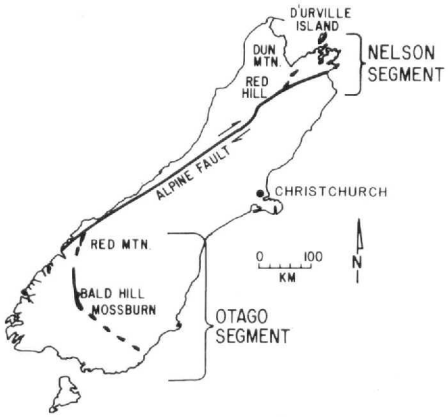

Figure 1. The Dun Mountain ophiolite belt, South Island, New Zealand.

Coleman (1962, 1966), from observations of the mineral assemblages at the ultramafic contact, estimated P-T conditions of low temperature and high pressure, which implies an origin other than igneous intrusion or load metamorphism. He proposed that Dun Mountain was emplaced into its present location as a cold tectonic intrusion. Blake and Landis (1973) further developed this hypothesis and concluded that Dun Mountain is an allochthonous block in a mélange that forms part of an ophiolite suite. Coombs and others (1976), Hunt (1978), and Davis and others (1980) also concluded that Dun Mountain is the ultramafic portion of an ophiolite.

This paper presents new data on the internal structure of Dun Mountain and evaluates the data in terms of the origin of the ultramafic rocks.

GEOLOGIC SETTING

The Dun Mountain ophiolite belt (Fig. 1), consisting of mafic and ultramafic rocks, is a major geologic feature of the South Island of New Zealand. It is divided into two segments separated by the Alpine Fault, a northern or Nelson Belt and a southern or Otago Belt. The two segments, considered to once have been continuous, have been separated by a 480-km dextral shift on the Alpine Fault (Wellman, 1948). Geophysically, both segments are characterized by strong positive magnetic anomalies (Hatherton, 1969).

The Nelson segment of the ophiolite belt consists of a band of serpentinite, dunite, and harzburgite, varying in width from 0 to ~8 km; this is bordered to the west by discontinuous segments of gabbro and mafic volcanics. In the northernmost portion of the Nelson segment at D'Urville Island, the ultramafic rocks consist of a serpentinite mélange (Coleman, 1966). Al-

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tered dolerites and mafic volcanics are common on the western border of the serpentinite. Dun Mountain is one of two relatively unserpentinized sections of the Nelson segment, the other being Red Hills, which is cut off on its southern margin by the Wairau Fault, a branch of the Alpine Fault (Fig. 1). With more than 1 km of exposed vertical section and an outcrop area of ~110 km^2, the Red Hills massif is the largest and best-exposed ultramafic of the Nelson segment. At Red Hills, numerous faults bound and crosscut the ultramafic massif (Walcott, 1969) and gravity studies (Malahoff, 1965) indicate a total thickness of <4 km, which suggests that the base of the massif is also in fault contact.

To the south and on the opposite side of the Alpine Fault, the Otago segment of the Dun Mountain ophiolite belt consists of several ultramafic massifs, often with associated mafic rocks. The northernmost ultramafic massif is that of the Cascade River–Martyr Hill region, which, like Red Hills, is truncated by the Alpine Fault (Fig. 1). Samples collected by the author from this region show variable serpentinization and strong tectonite fabrics. Red Mountain (Coombs and others, 1976; Sinton, 1977), located south of the Cascade River–Martyr Hill massifs, is the best-preserved ophiolite section of the Dun Mountain belt. The mafic sequence contains pillow basalts, a dike complex which is not sheeted, and a gabbro section often in fault contact with ultramafic rocks consisting primarily of harzburgite and dunite. Similar rocks occur ~30 km south at Cow Saddle.

Farther south, the ophiolite belt consists of a series of mélanges containing inclusions of spilite, diabase, gabbro, and metasedimentary rocks in a matrix of argillite, spilite, and serpentinite. In the Bald Hill area, an attenuated crustal section consisting of spilitic lavas, a dike complex, and massive gabbro is believed to have undergone tectonic thinning (Coombs and others, 1976). Southeast of Mossburn (Fig. 1), the ophiolite belt consists of a tectonic mélange of diabase, spilite, gabbro, sedimentary rocks, and felsic igneous rocks in a serpentinite matrix (Coombs and others, 1976).

The geology in the vicinity of Dun Mountain modified from maps of Lauder (1965), Coleman (1966), Hunt (1978), and Davis and others (1980) is shown in Figure 2. Dun Mountain (elevation 1,129 m) contains relatively good exposures, over an ~2 km^2 area, of fresh harzburgite and dunite surrounded by serpentinite (Reed, 1959). On the northwest flank of Dun Mountain, a narrow band of serpentinite, ~1 km in width, extends to the northeast and southwest. Foliations in the serpentinite are generally parallel to the strike of the band and dip steeply to the southeast or northwest. To the

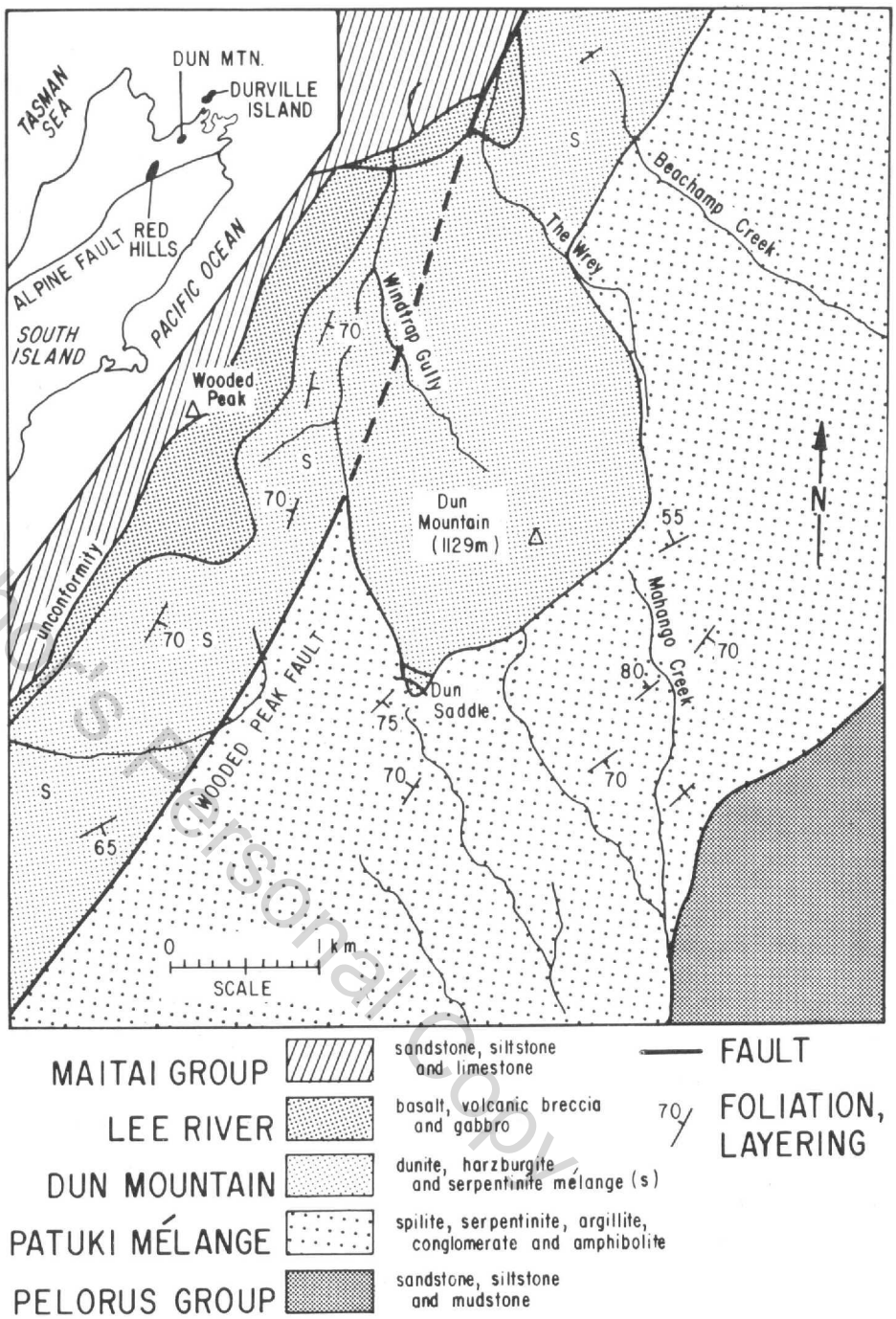

Figure 2. Geology in the vicinity of Dun Mountain.

northwest of the serpentinite and on the southeast side of Wooded Peak, there is a belt of mafic igneous rocks that with the ultramafic rocks forms the ophiolite belt. The mafic rocks were mapped as the Little Twin Spilite by Lauder (1965) and were included as part of the Te Anau Group. Waterhouse (1964) and Walcott (1969) referred to these as part of the Lee River Group. Davis and others (1980) subdivided the Lee River Group in the vicinity of Dun Mountain into the Tinline Formation, consisting of massive gabbro, microgabbro, and metamorphosed mafic dikes and sills, and the Glennie Formation, containing metabasalt of greenschist-facies grade. Unconformably overlying, and northwest of, the Lee River Group, there are late Permian limestones, siltstones, and sandstones of the Maitai Group (Fig. 2).

Bounded on the northwest by the Wooded Peak Fault and bordering Dun Mountain on its southwestern, southern, and eastern flanks, there is a belt of mélange, generally 2 to 4 km wide,

that trends northeast-southwest and consists of a sheared serpentinite matrix and blocks of argillite, spilite, conglomerate, and amphibolite. The inclusions were described by Bell and others (1911), Waterhouse (1959), and Coleman (1966). Along with the Dun Mountain ultramafic rocks and the Lee River Group, the mélange, referred to as the Patuki Mélange by Davis and others (1980), has often been mapped as a unit termed the "mineral belt" (see Bell and others, 1911; Battey, 1960; Coleman, 1966). Farther to the southeast and in fault contact with the mélange, the Peloris Group consists of graywacke, sandstone, argillite, and siltstone of possible Carboniferous age (Walcott, 1969).

MACROSCOPIC STRUCTURE

The summit of Dun Mountain is elongated northeast-southwest. In cross section along a northwest-southeast profile, it is asymmetrical, with a long, relatively gentle slope to the northwest and a steep slope on the southeast. Rusty-weathered dunite and harzburgite are well exposed along the crest of the mountain. Elsewhere, the surface of the mountain is covered with large boulders, many of which are not in place. In the northern portion of the mountain and on the northwest and southwest sides of the summit, major slumping is common, often with rotations about a northeast-southwest axis (that is, parallel to the elongation of the mountain). Hunt (1974), in his study of rock magnetism of Dun Mountain, confined his sampling to the summit plateau and its northeast and southwest slopes because of the slumping. Similar caution is necessary for any structural analysis of the Dun Mountain rocks.

Previous descriptions of the gross structure of Dun Mountain, as well as visible structures in outcrops, differ markedly from one another. Turner (1942) described three types of rocks from Dun Mountain: (1) banded dunite consisting of black layers of chromite a few millimetres in thickness alternating with olivine-rich bands; (2) nonfissile, nonbanded rocks that break irregularly; and (3) fissile, nonbanded dunite. Battey (1960), on the other hand, concluded from his study of Dun Mountain that "the rocks have no visible schistosity, or fissility, and the grains are on a whole equidimensional." Coleman (1966) reported a crude layering of dunite and harzburgite within Dun Mountain with a 40° dip to the east. Lauder (1965), however, proposed that Dun Mountain contains concentric vertical layers of dunite and harzburgite that were produced by the accumulation of phenocrysts in a volcanic pipe. A "crude concentric outcrop pattern" of dunite and harzburgite on Dun Mountain was also reported by Davis and others (1980). The cryptic, cylindrical layering proposed by Lauder (1965) was challenged by Walcott (1969). Mapping by the author also has uncovered little evidence supporting the presence of concentric layering within Dun Mountain.

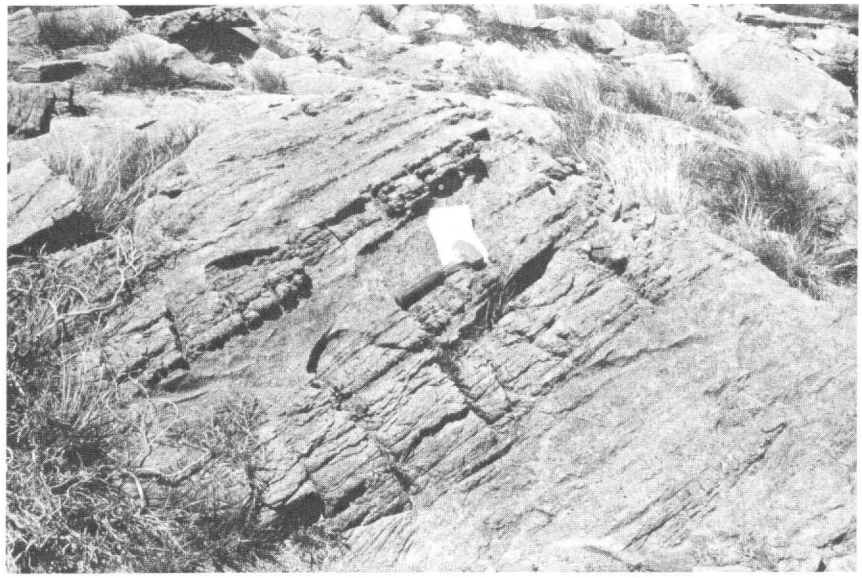

Figure 3. Foliation in Dun Mountain harzburgite.

The most common structure within Dun Mountain is a foliation produced by an elongation and flattening primarily of olivine and to a lesser extent of orthopyroxene and spinel. The foliation is strongly developed in many outcrops (Fig. 3), and even though weak in others it is

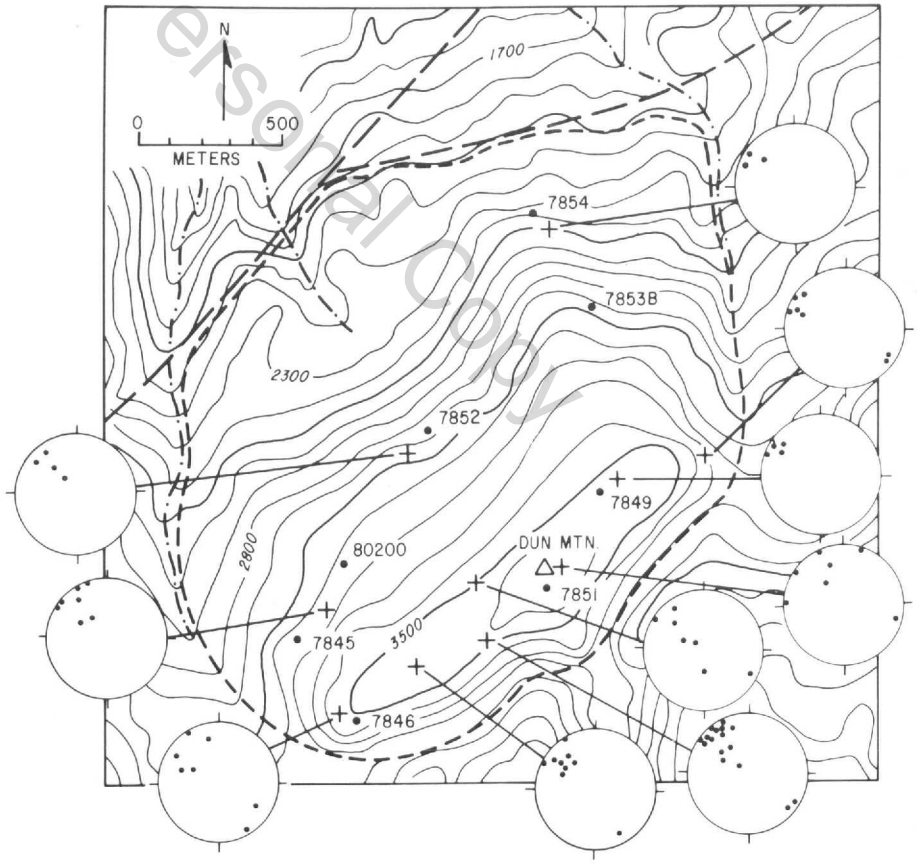

Figure 4. Normals to foliations plotted on lower-hemisphere projections and sample locations for petrofabric analyses.

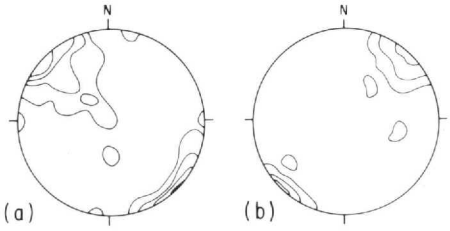

Figure 5. Lower-hemisphere projections of (a) 70 foliations and (b) 38 lineations from Dun Mountain. Contours 1%, 4%, 6%, and 8% per 1% area.

Figure 6. Elongated, kinked olivine grains from a 2.54-cm-diameter core. Olivine *a* axes maximum is east-west, and the *b* axes maximum is north-south. Note the obliquity on the foliation to the olivine *a* maximum.

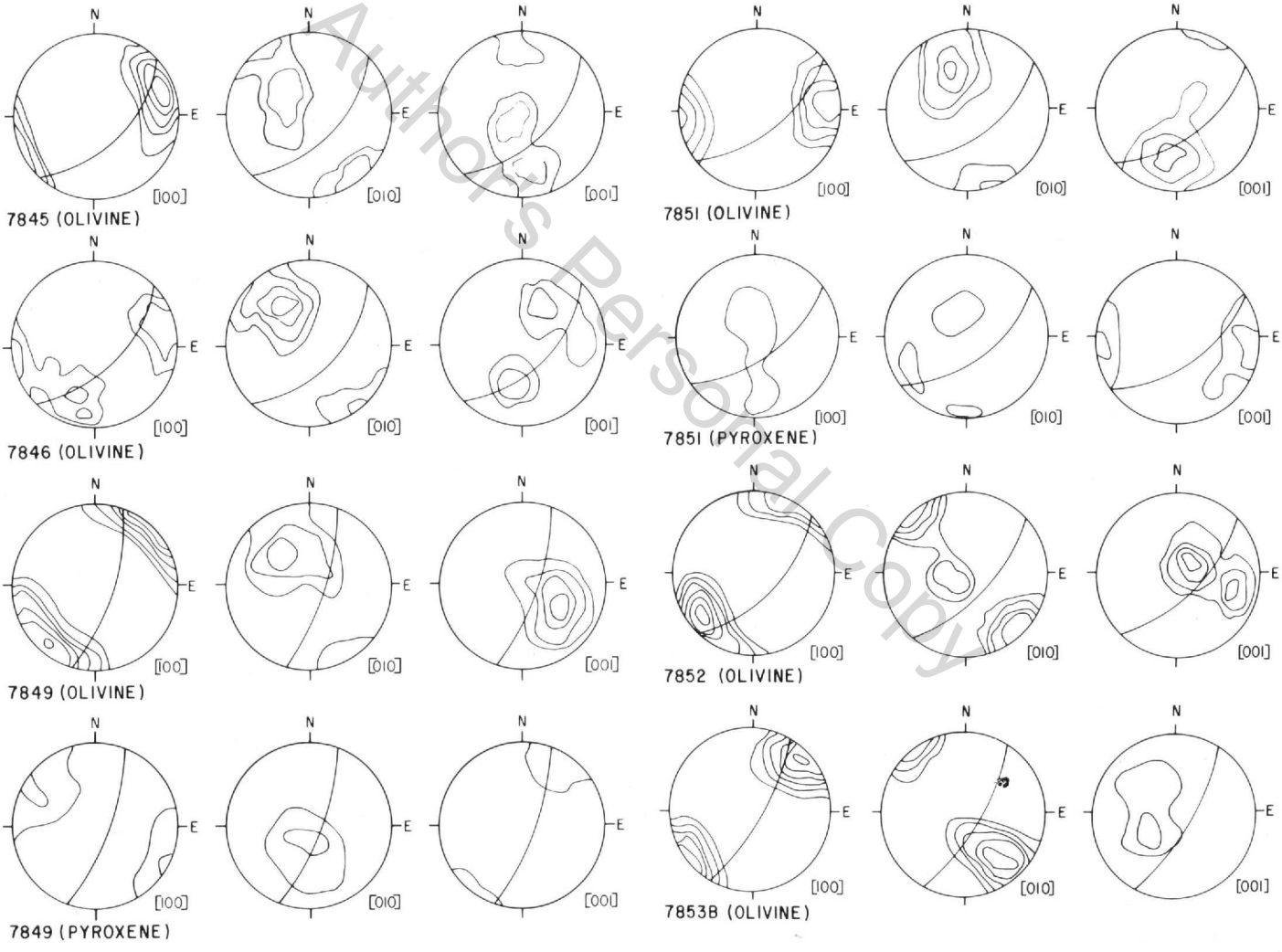

Figure 7. Equal-area, lower-hemisphere Kamb projections of [100], [010], and [001] axes of olivine and orthopyroxene. The projections are contoured in 2 σ intervals with the lowest contour = 4 σ, σ = 2.75, E = 3 σ, counting area A = 0.083. Foliations are shown as great circles. Chromite layering in sample 80200 is shown as a dashed line.

widespread. Recorded attitudes of foliations from nearby outcrops throughout the summit plateau and to the northwest at localities where the effects of slumping are minimal are fairly consistent (Fig. 4). A composite of foliations from Dun Mountain is contoured in Figure 5. The average strike is northeast-southwest and dips, in general, are quite steep to the southeast.

Although not as common as in Red Hills or Red Mountain, banding produced by alternating harzburgite and dunite layers as much as several centimetres in width is locally present. The banding is usually more conspicuous in outcrop than is foliation, because the olivine invariably weathers preferentially, leaving the pyroxene and spinel in relief on the weathered surface of the harzburgite. In Dun Mountain, the banding usually parallels the foliation. Although not common, isoclinal folds have axes parallel to lineations.

Banding produced by layers of chromite as much as a few centimetres in width alternating with dunite is also common, particularly in the southwest portion of the summit plateau. The chromite banding is usually discontinuous and approximately parallel to foliation.

Several types of lineations are common in the summit rocks of Dun Mountain. They are most readily seen on foliation surfaces and consist of elongated grains of orthopyroxene and olivine, spindle-shaped spinels, and "trains" of approximately equidimensional spinels. All lineations show a remarkable similarity in orientation, with a trend northeast-southwest and horizontal (Fig. 5).

MICROSCOPIC STRUCTURE

Examination of the Dun Mountain rocks in thin section demonstrates a tectonic origin for the ultramafic massif. Textures in the harzburgites and dunites are usually porphyroclastic and locally mylonitic. The olivine porphyroclasts have irregular grain boundaries and show a wide range in grain size (usually 2–8 mm). Thin sections cut normal to the foliation and parallel to lineation often show an abundance of elongated olivine grains that define the foliation (Fig. 6). In

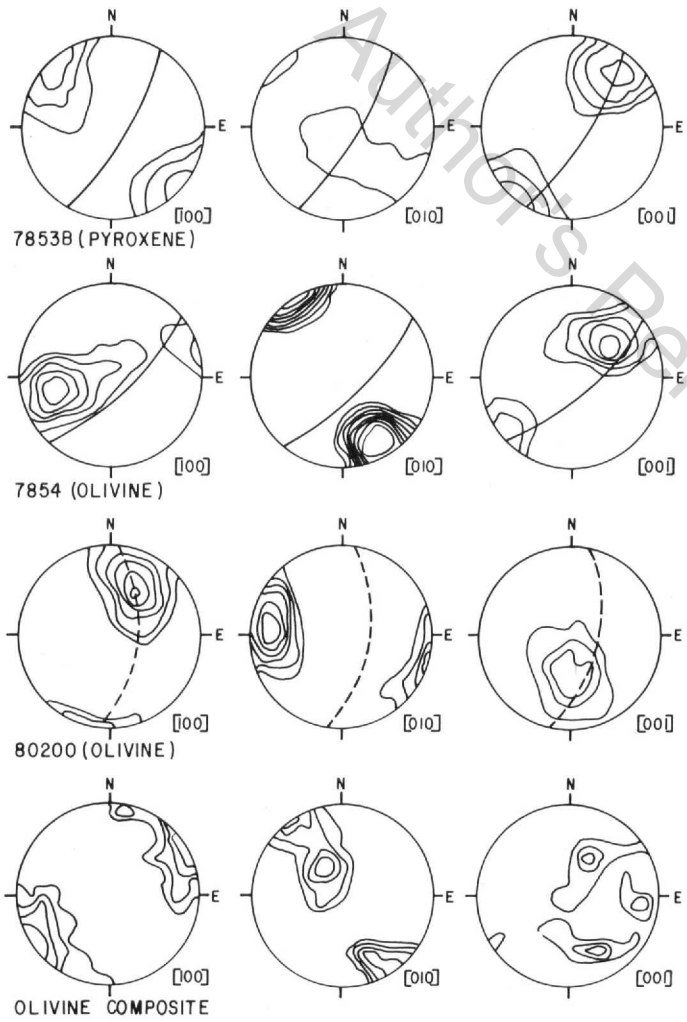

Figure 7. (*Continued*).

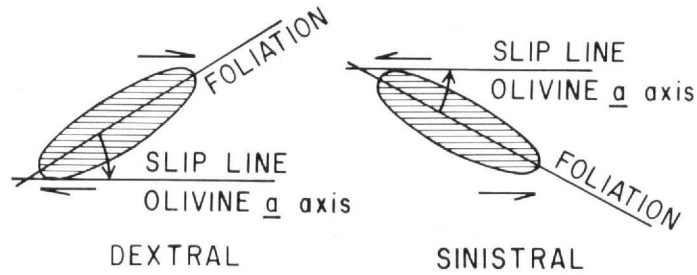

Figure 8. Shear sense in olivine tectonites obtained from the crystallographic orientation of olivine determined from petrofabric analyses and the elongation of olivine (Nicolas and Poirier, 1976).

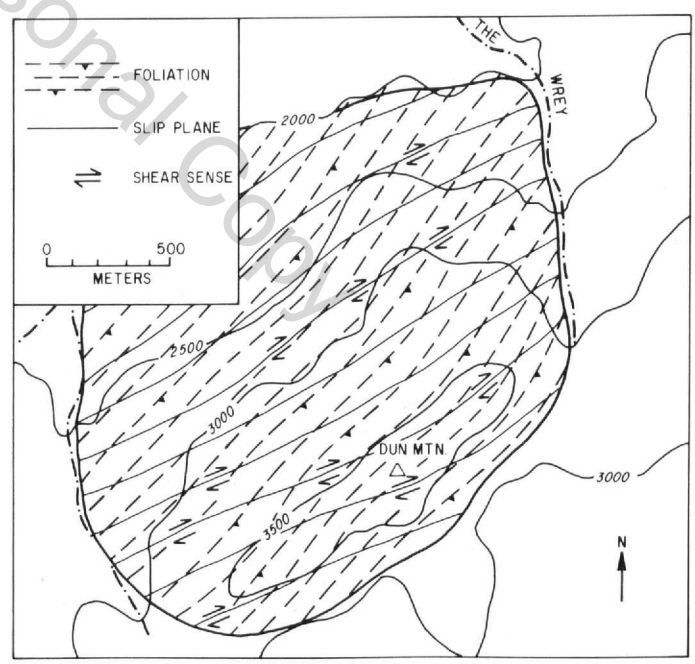

Figure 9. Schematic diagram illustrating measured shear sense and the approximate traces of foliations and olivine [010] slip planes.

many sections, approximately equidimensional olivine grains are present along with olivines that display a large aspect ratio. Undulatory extinction of olivine resulting from kinking and associated inhomogeneous slip (Raleigh, 1968) is common (Fig. 6). Locally, the ultramafic rocks contain stringers and patches of fine-grained recrystallized olivine and orthopyroxene. The stringers tend to parallel foliation.

Field-oriented samples were collected at several localities along the summit plateau and its northern slope (Fig. 4). Care was taken to avoid sampling from outcrops that possibly could have been affected by slumping. Thin sections were cut in a horizontal plane and preferred mineral orientations measured by using a 5-axis universal stage (Emmons, 1943) are presented in Figure 7.

The fabric diagrams show that olivine orientation is relatively uniform throughout Dun Mountain. Olivine *a* crystallographic axes show strong concentrations and tend to lie near horizontal in the northeast and southwest quadrants. The olivine *a* axes maxima lie close to the foliation planes and are approximately parallel to the lineations measured in the field. The olivine *b* crystallographic axes maxima are northwest-southeast and horizontal, and they fall near the poles of the foliations. In some samples, olivine *b* axes maxima and submaxima dip to the northwest. A strong olivine *b* crystallographic axis maxima is consistent with an origin by high-temperature plastic flow with slip on (010) in the [100] direction (Carter and Avé Lallemant, 1970; Nicolas and others, 1973). The olivine *b* axes submaxima observed in samples 7845 and 7852 suggest that the olivine $\{0k\ell\}$ [100] slip system (that is, pencil glide; Raleigh, 1968) was locally operative. Owing to the partial girdles of (010), it is likely that certain planes in the zone $\{0k\ell\}$ are preferred slip planes.

The P-T conditions required for the slip system $\{0k\ell\}$ [100] to be operative, as indicated by experimental studies at a strain rate of approximately $10^{-4}s^{-1}$, are pressures in the range of 5 to 20 kbar and temperatures in excess of 900 °C (Carter and Avé Lallemant, 1970). The active glide system (010) [100] requires higher temperatures. Natural deformations usually take place at much lower rates. Extrapolation to a representative geological strain rate of $10^{-14}s^{-1}$ indicates that slip on the systems $\{0k\ell\}$ [100] and (010) [100] occurs at temperatures above 350 °C (Carter and Avé Lallemant, 1970), which (from the oceanic geotherm of Clark and Ringwood, 1964) suggests depths of origin >15 km away from spreading centers.

Shear sense in ultramafic tectonites can be estimated from the obliquity of the olivine *a* axes maximum relative to the lineation (X axis of the finite strain ellipsoid) or the foliation (Darot and Boudier, 1975; Nicolas and Poirier, 1976). This is illustrated in Figure 8 for the slip system (010) [100]. The lineation is defined by the elongation of the olivine crystals, and the slip lines are within the (010) slip planes and parallel to crystallographic *a*. Note that the sense of shear applies to the plastic-flow plane [(010) in Fig. 8], not to the foliation.

Foliations and lineations measured from the hand samples and from thin sections cut in planes containing the olivine *a* and *b* axes maxima are shown in Figure 7. In sample 80200, foliation was obscured by bands of chromite that lie approximately parallel to the plane defined by the olivine *a* and *c* axes maxima. In all samples measured, shear senses are consistent, indicating dextral shear. The northern portion of Dun Mountain has been displaced to the east relative to the southern portion (Fig. 9).

Although the orientation of orthopyroxene is quite weak, the petrofabric analyses (Fig. 7) do show systematic relationships with the olivine orientation data. The orthopyroxene *c* crystallographic axes maxima parallel the olivine *c* axes maxima, with the orthopyroxene *a* and *b* axes usually coinciding with *b* and *c* of olivine, respectively. The (100) plane of enstatite lies in the foliation with crystallographic *c* subparallel to lineations. A similar relationship between olivine and orthopyroxene petrofabrics, foliation, and lineation appears to be common in many peridotites within ophiolites (Christensen and Lundquist, 1982).

The orientations of olivine *a* axes are, in general, in excellent agreement with those determined by Battey (1960), which show strong, essentially horizontal concentrations northeast-southwest. Preferred orientation patterns of olivine *b* axes presented by Battey (1960) show two distinct maxima, one nearly vertical and the other dipping to the northwest. The fabrics presented here, however, indicate that the olivine *b* axes vary from a steep northwesterly dip to a horizontal and northwest-southwest orientation, which is consistent with olivine *b* axes maxima being approximately perpendicular to foliations (Fig. 5). As discussed earlier, the double maxima of olivine *b* axes observed in specimens 7845 and 7852 may have originated from pencil glide, with certain planes in the zone $\{0k\ell\}$ acting as preferred slip planes.

SEISMIC ANISOTROPY

The existence of compressional-wave seismic anisotropy in the upper oceanic mantle has provided an important constraint on the composition of the upper mantle. Upper-mantle velocities are high, parallel or subparallel to spreading directions (Morris and others, 1969; Keen and Barrett, 1971; Raitt and others, 1971), with observed anisotropy generally varying from 3% to 8% (0.3 to 0.7 km/s maximum difference in velocity in a horizontal plane). Eclogites are usually isotropic or nearly isotropic, whereas laboratory measurements of seismic velocities in peridotite and dunite (Birch, 1961; Christensen, 1966) show strong anisotropies, which correlate well with petrofabric studies and the seismic anisotropy of single-crystal olivine (Verma, 1960). Upper-mantle anisotropy thus most likely originates from the preferred orientation of olivine crystals in a peridotite upper mantle, as originally suggested by Hess (1964).

If the Dun Mountain ultramafic rocks originated as oceanic upper mantle, their seismic anisotropy should be similar to observed oceanic upper-mantle anisotropy. Recent studies of the ultramafic portions of the Bay of Islands ophiolite, Newfoundland (Christensen and Salisbury, 1979), and the Samail ophiolite, Oman (Christensen and Smewing, 1981), found anisotropies indistinguishable from upper-mantle seismic anisotropy. For these ophiolites, furthermore, the crustal sections are complete, and it was possible to demonstrate that the directions of maximum velocities coincide with spreading directions inferred from sheeted-dike orientations.

Velocity anisotropy in Dun Mountain has been calculated at a confining pressure of 2 kbar from the composite fabric diagram in Figure 7, using the computer program of Crosson and Lin (1971). From the single-crystal elastic constants of olivine, their pressure derivatives, and the universal-stage orientation data of each olivine crystal in the composite, the program calculates the contribution of each mineral to the rock velocities in specified directions. One compressional-wave velocity and two shear-wave velocities, with perpendicular polarization directions, are given as output for each specified propagation direction. These velocities are then contoured to show total anisotropy patterns in three dimensions within Dun Mountain. Several studies (Crosson and Lin, 1971; Carter and others, 1972) found excellent agreement between the calculated and the laboratory-measured velocity anisotropy.

The calculations for the Dun Mountain rocks are shown in Figure 10 in lower-hemisphere projections. Contoured diagrams are given for compressional-wave velocity (V_p), the maximum shear-wave velocity ($V_s$max), the minimum shear-wave velocity ($V_s$min), the difference in shear-wave velocities (ΔV_s), Poisson's ratio calculated from V_p and V_s max, and Pois-

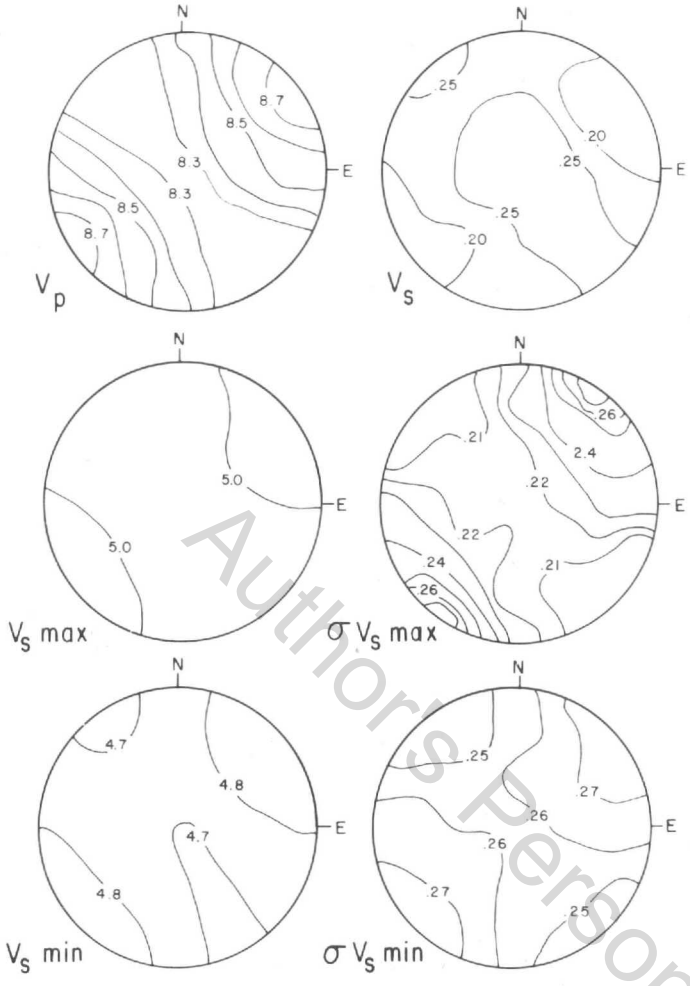

Figure 10. Seismic anisotropy calculated for Dun Mountain (see text).

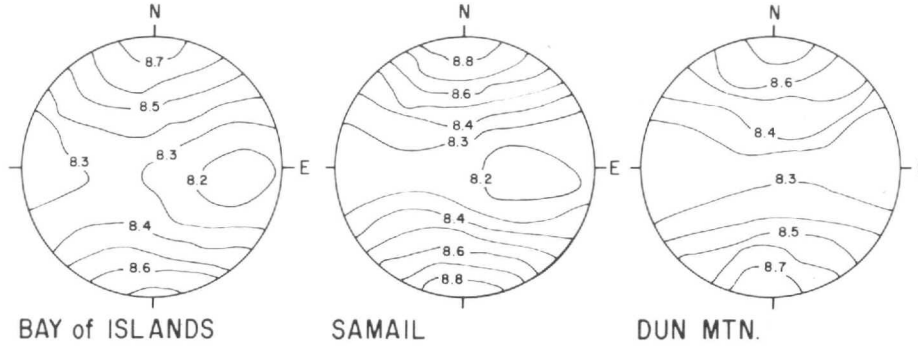

Figure 11. Compressional-wave velocities in km/s at 2 kbar calculated for the North Arm massif, Bay of Islands ophiolite, Newfoundland (Christensen and Salisbury, 1979); the Samail ophiolite, Oman (Christensen and Smewing, 1981); and Dun Mountain, New Zealand. All contours have been rotated, so that the maximum velocities are approximately north-south and horizontal. The spreading centers strike approximately east-west, with spreading directions north-south.

son's ratio calculated from V_p and $V_s$min. The compressional-wave velocity anisotropy is in good agreement with upper-mantle seismic anisotropy (Raitt and others, 1971) and with anisotropy observed in other ophiolites (Fig. 11). This strongly supports an oceanic upper-mantle origin for the Dun Mountain ultramafic massif.

On the basis of anisotropy alone, it is impossible to distinguish suboceanic mantle from subcontinental mantle, because seismic anisotropy has also been observed in mantle beneath the continents (Bamford, 1973; Vetter and Minster, 1981). The association of many ophiolite rock types with the Dun Mountain ultramafic massif (Coombs and others, 1976; Davis and others, 1980), however, strongly favors an oceanic origin.

SUMMARY AND CONCLUSIONS

Structurally, the ultramafic rocks of Dun Mountain are tectonites with macroscopic structures and microscopic textures indicative of high-temperature solid-state flow. Foliation, which originates from flattening and alignment of olivine, enstatite, and spinel, is often visible in the field. The foliation on the average strikes northeast-southwest and dips steeply southeast. The summit plateau of Dun Mountain is elongated parallel to the strike of the foliation. Lineations that define a stretching direction lie within the foliation, forming a horizontal maximum that strikes northeast-southwest.

Porphyroclastic textures, frequent elongation of olivine grains, abundant kink banding, and local mylonitic textures are interpreted to have formed in the oceanic upper mantle. Preferred orientations of olivine determined from petrofabric analyses suggest that the olivine {0kℓ} [100] and (010) [100] slip systems were active, which in turn, from P-T considerations, indicates an upper-mantle deformation for the ultramafic rocks. Shear sense in the ultramafic rocks determined by the obliquity of the olivine *a* axis maxima to the foliation and lineation is dextral.

Battey (1960), in his study of petrofabrics of Dun Mountain rocks, concluded that the olivine orientation was probably produced by the same tectonic forces responsible for folding of the enclosing rock units. Battey cited a regional strike of N55°E and axial plunges of folds of 12° to 15° at N50°E to N56°E in the Maitai Formation. Lineations within the dunite and peridotite show a well-defined horizontal maximum at N45°E (Fig. 5). The angular difference between the orientations of the two lineations is small and may very well be within the combined errors of estimate of their attitudes. The lineations, however, could not have been imposed during

the same deformational event, because structures in the Dun Mountain ultramafic rocks are clearly related to the olivine fabrics, which originated at much higher temperatures by subsolidus flow in the upper mantle.

The preferred orientation of olivine within Dun Mountain is responsible for strong seismic anisotropy, the magnitude of which is typical of that observed in oceanic upper mantle occurring on the flanks of major oceanic ridges. The symmetry and magnitude of the anisotropy furthermore are similar to those present in the upper-mantle portion of complete ophiolite sections from Oman and Newfoundland in which the crustal sections have velocity profiles similar to those of normal oceanic crust (Christensen and Salisbury, 1979; Christensen and Smewing, 1981). In the Oman and Newfoundland ophiolites, the maximum compressional-wave velocity, which corresponds to the maximum concentration of olivine *a* axes, is approximately normal to the sheeted dikes. This suggests that relative to the present attitude of the Dun Mountain ultramafic massif, the paleoridge strikes approximately N40°W. There is no way of confirming this observation because the Dun Mountain ultramafic rocks are completely detached from the crustal rocks.

To date, most information on upper-mantle seismic anisotropy derives from refraction studies in major ocean basins, although there is some evidence for the presence of similar anisotropy in marginal basins (Shor and Fornari, 1976). It thus appears, at present, that the pattern of anisotropy will not discriminate between upper mantle formed at a spreading ridge and upper mantle formed in a marginal basin.

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