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Fabric, Seismic Anisotropy, and Tectonic History of the Twin Sisters Dunite, Washington

ABSTRACT

Olivine orientation and seismic anisotropy at confining pressures of 0.1 to 10.0 kb have been studied for 14 samples collected from the Twin Sisters dunite. At 10 kb, the dunites show differences in compressional wave velocities with propagation direction ranging from 0.03 to 0.92 km/sec. All samples were geographically oriented in the field, and the measured velocities have been related to the geographic orientations. The results show a complex but definite pattern of anisotropy throughout the body in which the slow velocities tend to be horizontal and normal to the elongation of the body. Mean velocities in a vertical direction are slightly higher than mean north-south velocities.

The anisotropy is clearly related to preferred olivine orientation. Petrofabric studies of the field-oriented samples show concentrations of olivine *b* crystallographic axes parallel to slow velocities. High velocities have been measured parallel to concentrations of olivine *a* axes. The fabric studies further indicate that the olivine *b* axes throughout the body show a strong tendency to lie horizontal in a northeast-southwest to east-west direction.

The fabric of the Twin Sisters body is interpreted as having originated by recrystallization accompanying flow within the upper mantle. Locally this fabric has been modified by cataclasis and plastic flow. The dunite body appears to have been transported from the mantle as a solid along a major thrust fault.

INTRODUCTION

Beginning with the earliest investigations of olivine fabric (Andreatta, 1934; Ernst, 1935; Phillips, 1938), it was found that olivine in dunites and peridotites commonly shows strong preferred orientation. The origin of this preferred orientation has been highly debated ever since. Due to recent interest in sea-floor spreading and the advancement of plate tectonics, an understanding of preferred olivine orientation has taken on new importance. Hess (1964), Raitt and others (1969), and Meyer and others (1969) found strong evidence suggesting seismic anisotropy in the upper mantle. Observations of P_n velocities in the northeastern Pacific show velocity variations with profile direction from 0.3 km/sec to 1.0 km/sec. The most probable cause of this anisotropy is preferred mineral orientation in the upper mantle. Laboratory measurements have shown that many common rocks are anisotropic to compressional wave propagation (Birch, 1960; Christensen, 1965, 1966). In particular, measurements at upper-mantle pressures in dunites and peridotites have shown that anisotropy in these rocks originates from preferred olivine orientation (Birch, 1961; Christensen, 1966).

Once seismic anisotropy was discovered in the upper mantle, it became apparent that anisotropy may become important in understanding upper mantle flow. Several models already have been proposed for olivine orientation in the upper mantle (Hess, 1964; Sugimura and Uyeda, 1966; Christensen and Crosson, 1968; Francis, 1969; Ave'Lallemant and Carter, 1970). With the accumulation of new seismic data designed specifically to detect variations in velocities with azimuth and new experimental data bearing on the relationship of anisotropy to mineral orientation, it will become possible to examine the implications of these models and discard those that are not acceptable.

In this paper, the relationships between olivine fabric and seismic anisotropy are examined for 14 rocks collected from the Twin Sisters dunite. The question of whether large bodies of dunite or peridotite can be anisotropic to seismic wave propagation is also considered. The results are interpreted in terms of their significance in understanding mantle anisotropy and the deformational history of the Twin Sisters dunite.

Geological Society of America Bulletin, Vol. 82, p. 1681-1694, 19 figs., June 1971

GEOLOGIC SETTING AND PETROGRAPHY

The Twin Sisters dunite is located in Whatcom County, Washington, 39 km east of Bellingham and 29 km south of the Canadian border. The dunite body extends in a north-northwest direction for approximately 16 km and averages 5.5 km in width.

Petrographic studies by Gaudette (1963) and Ragan (1963) report an average of 93 percent olivine, 5 percent enstatite, and 2 percent chromite for the fresh dunite. Chemical analyses of olivine in the Twin Sisters dunite (Moen, 1969, p. 37) show that the olivine contains about 10 percent fayalite. Serpentinite is sometimes present along the margins of the body as a rind that is as much as .5 km in width. In addition, serpentine is common along fracture zones in the interior of the body. Chromite occurs within the body as disseminated grains and as discontinuous veins and lenses.

Ragan (1963) recognized several different textures within the Twin Sisters dunite, including a texture consisting of coarse, anhedral olivine grains with irregular interlocking boundaries which he interpreted as originating early in the history of the dunite by metamorphic recrystallization. Superimposed upon this earlier texture are deformational features consisting of zones of finely granulated olivine, olivine crystals with abundant kink banding and bent enstatite crystals. Detailed petrographic studies (Ragan, 1963) also suggest that some of the granulated olivine has been recrystallized and often has undergone a second stage of cataclasis. All of these textural features have been observed in samples included in the present study.

The regional geology in the vicinity of the Twin Sisters dunite is described in detail by Misch (1966). Features pertinent to the present study are briefly summarized below. A slightly modified version of a geologic map by Misch (1966, p. 121) is given in Figure 1.

The crystalline core of the Northern Cascades consists primarily of the Skagit Metamorphic Suite which is composed predominantly of schist and migmatitic gneiss of metamorphic grade ranging from greenschist to amphibolite facies. The age of metamorphism of the Skagit Suite is pre-Jurassic (Misch, 1966). To the west, separated from the Skagit Metamorphic Suite by the Straight Creek Fault, are two thrust plates which overlie the Jurassic-Cretaceous Nooksack Formation. The lower or Church Mountain thrust plate is composed primarily of upper Paleozoic eugeosynclinal rocks ranging from graywackes, volcanics, and subordinate limestones to slates and phyllites. Rocks of the upper or Shuksan thrust plate are pre-Jurassic phyllites, blueschists, and greenschists. The thrust plates are locally overlain by early Tertiary arkosic sandstones, conglomerates and shales, the Mt. Baker volcanics, and recent alluvium.

The Twin Sisters dunite is located near the sole of the Shuksan thrust plate (Fig. 1). Ragan (1963) originally mapped a high-angle fault along the southeastern boundary of the dunite and postulated that the fault was related to the emplacement of the dunite body. Later work by Misch and students (Misch, 1966; 1970, personal commun.) has shown that this fault is actually the Shuksan thrust which has been folded by Tertiary tectonic activity so that it dips westerly. Thompson (1963), from a preliminary gravity traverse across the Twin Sisters range, reported a complete Bouguer anomaly 29 mgal higher than the surrounding region and concluded that the thickness of the Twin Sisters body is not much greater than the total vertical exposure of dunite (Fig. 2). A later detailed gravity survey (Christensen, in prep.) has shown that the base of the dunite is located at a fairly constant depth throughout the body and probably does not extend below sea level.

The geometry of the Twin Sisters body and its geologic location suggest that it is a large tectonic slice associated with the Shuksan thrust. Misch (1966) reported numerous ultramafics in the imbricate zone below this thrust which he interpreted as being tectonically emplaced and mantle derived. In addition, the Shuksan thrust commonly contains slices of crystalline basement rock which also verify a deep origin for the thrust. It is thus quite probable that the Twin Sisters dunite is mantle derived and that its emplacement is related to Cretaceous thrusting. A mantle origin for the dunite was also proposed by Ragan (1963).

FABRIC AND VELOCITY DATA

Sampling

Samples of dunite weighing 20 to 30 lbs were collected from 14 locations throughout the Twin Sisters range. Each sample was field oriented and selected to be as free of fractures

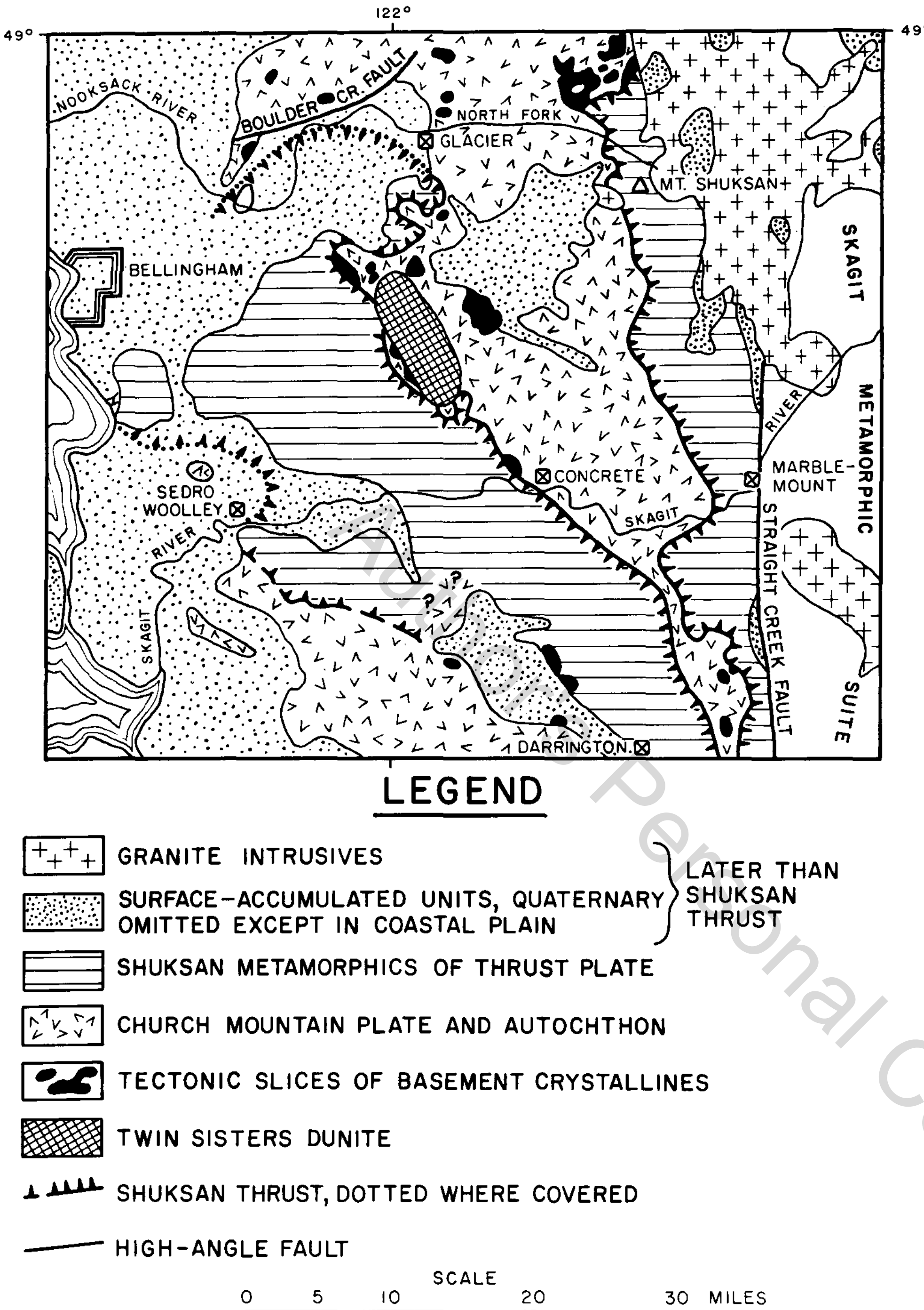

Figure 1. Geologic map in the vicinity of the Twin Sisters dunite (*after* Misch, 1966).

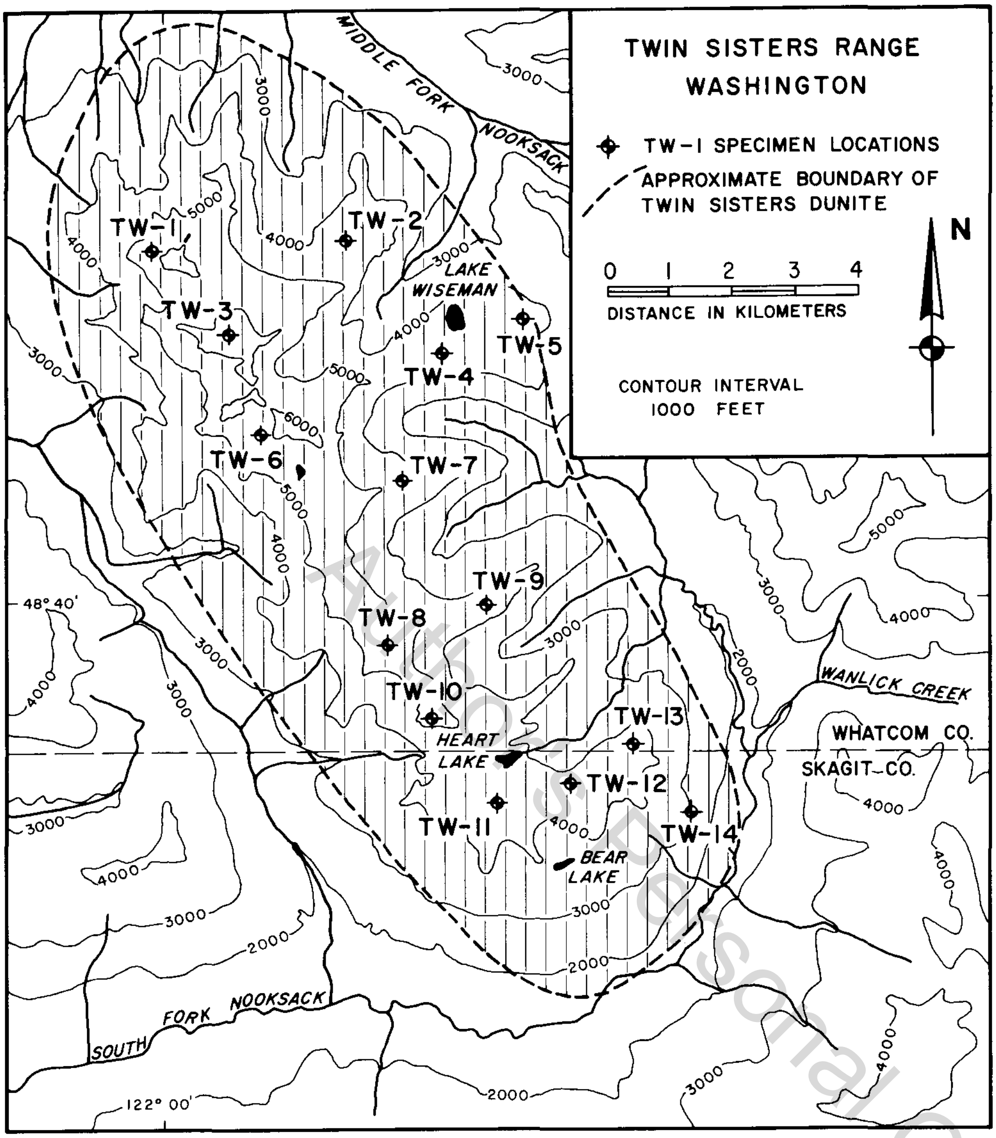

Figure 2. Map of the Twin Sisters dunite, showing sample localities.

and chromite as possible. Locations of the samples are shown in Figure 2.

Compressional Wave Velocities

Compressional wave velocities as a function of pressure are given in Table 1. The velocities were measured by a pulse transmission technique similar to that described by Birch (1960) for three mutually perpendicular cylinders 2.5 cm in diameter and 5.3 cm in length from each sample. The axes of the cores were oriented in north-south, east-west, and vertical directions. The velocities are accurate to ± 0.5 percent (Christensen and Shaw, 1970). The precision of the measurements is better than 0.3 percent.

The pressure system utilizes a two-stage pumping technique with a pressure intensifier. The pressure medium is a low-viscosity petroleum. Pressure is measured to ± 1 percent by the use of a calibrated manganin coil.

Velocity-Density Relationships

The velocities of some of the samples are significantly lowered by serpentinization. This

TABLE 1. COMPRESSIONAL WAVE VELOCITIES AS A FUNCTION OF PRESSURE

Sample	Orien-tation	Density gcm^{-3}	V_P, km/sec p = 0.20 kb	p = 0.60 kb	p = 1.0 kb	p = 2.0 kb	p = 4.0 kb	p = 6.0 kb	p = 8.0 kb	p = 10.0 kb
TW-13	N.-S.	3.058	6.992	7.124	7.171	7.259	7.370	7.450	7.508	7.548
	E.-W.	3.109	6.619	6.820	6.919	7.086	7.165	7.323	7.382	7.425
	V	3.065	6.713	6.932	7.055	7.205	7.365	7.451	7.525	7.558
	Mean	3.077	6.775	6.958	7.048	7.183	7.300	7.408	7.472	7.510
TW-7	N.-S.	3.167	7.302	7.351	7.385	7.434	7.537	7.598	7.645	7.675
	E.-W.	3.115	7.294	7.324	7.365	7.405	7.460	7.491	7.515	7.530
	V	3.120	7.228	7.279	7.313	7.380	7.449	7.492	7.532	7.560
	Mean	3.134	7.275	7.318	7.354	7.406	7.482	7.527	7.564	7.588
TW-6	N.-S.	3.161	7.358	7.424	7.514	7.610	7.727	7.802	7.847	7.871
	E.-W.	3.144	6.973	7.052	7.077	7.143	7.245	7.316	7.379	7.424
	V	3.193	7.694	7.813	7.831	7.908	8.008	8.070	8.112	8.141
	Mean	3.166	7.342	7.430	7.474	7.554	7.660	7.729	7.779	7.812
TW-10	N.-S.	3.227	7.860	7.957	7.997	8.053	8.130	8.181	8.215	8.240
	E.-W.	3.226	7.513	7.547	7.584	7.605	7.660	7.700	7.729	7.750
	V	3.264	7.769	7.898	7.976	8.098	8.197	8.262	8.309	8.345
	Mean	3.239	7.714	7.801	7.852	7.919	7.996	8.048	8.084	8.112
TW-3	N.-S.	3.224	7.750	7.831	7.856	7.900	7.955	7.986	8.011	8.030
	E.-W.	3.248	7.730	7.768	7.799	7.843	7.905	7.936	7.963	7.980
	V	3.255	8.423	8.477	8.503	8.544	8.598	8.620	8.637	8.643
	Mean	3.242	7.968	8.025	8.053	8.096	8.153	8.181	8.204	8.218
TW-1	N.-S.	3.251	8.341	8.431	8.478	8.549	8.640	8.693	8.729	8.752
	E.-W.	3.247	7.716	7.781	7.823	7.869	7.948	7.998	8.033	8.056
	V	3.235	7.565	7.644	7.663	7.717	7.796	7.849	7.885	7.905
	Mean	3.244	7.874	7.952	7.988	8.045	8.128	8.180	8.216	8.238
TW-12	N.-S.	3.271	7.524	7.765	7.856	7.925	8.022	8.069	8.100	8.120
	E.-W.	3.281	7.739	7.854	7.896	7.952	8.034	8.077	8.105	8.120
	V	3.293	8.729	8.801	8.836	8.879	8.938	8.982	9.013	9.040
	Mean	3.282	7.997	8.140	8.196	8.252	8.331	8.376	8.406	8.427
TW-2	N.-S.	3.275	7.420	8.094	8.248	8.345	8.450	8.510	8.550	8.576
	E.-W.	3.280	7.586	7.798	7.880	7.950	8.028	8.080	8.114	8.137
	V	3.298	8.028	8.174	8.243	8.288	8.354	8.407	8.443	8.470
	Mean	3.284	7.678	8.022	8.124	8.194	8.277	8.332	8.369	8.394
TW-9	N.-S.	3.298	7.963	8.273	8.392	8.227	8.289	8.322	8.341	8.354
	E.-W.	3.294	7.954	8.009	8.034	8.064	8.107	8.137	8.161	8.179
	V	3.287	8.275	8.454	8.522	8.570	8.636	8.684	8.715	8.733
	Mean	3.293	8.064	8.245	8.316	8.287	8.344	8.381	8.406	8.422
TW-14	N.-S.	3.294	7.656	7.820	7.860	7.993	8.140	8.223	8.267	8.282
	E.-W.	3.297	7.711	7.843	7.893	7.951	8.029	8.076	8.102	8.115
	V	3.292	8.358	8.469	8.522	8.592	8.687	8.748	8.783	8.803
	Mean	3.294	7.908	8.044	8.092	8.179	8.285	8.349	8.384	8.400
TW-5	N.-S.	3.297	8.300	8.394	8.455	8.499	8.562	8.601	8.630	8.650
	E.-W.	3.286	7.907	7.956	7.982	8.031	8.096	8.132	8.161	8.183
	V	3.298	7.884	7.939	7.973	8.023	8.096	8.145	8.178	8.200
	Mean	3.294	8.030	8.096	8.137	8.184	8.251	8.293	8.323	8.344
TW-8	N.-S.	3.296	8.707	8.739	8.771	8.802	8.869	8.908	8.940	8.963
	E.-W.	3.298	7.985	8.055	8.076	8.122	8.179	8.224	8.249	8.262
	V	3.296	8.169	8.224	8.252	8.300	8.369	8.407	8.438	8.460
	Mean	3.297	8.287	8.339	8.366	8.408	8.472	8.513	8.542	8.562
TW-4	N.-S.	3.297	8.417	8.462	8.494	8.541	8.605	8.638	8.668	8.692
	E.-W.	3.294	7.896	7.942	7.967	8.050	8.051	8.083	8.104	8.118
	V	3.310	8.429	8.491	8.523	8.564	8.623	8.666	8.695	8.714
	Mean	3.300	8.247	8.298	8.328	8.385	8.426	8.462	8.489	8.508
TW-11	N.-S.	3.308	8.038	8.183	8.245	8.322	8.410	8.456	8.485	8.502
	E.-W.	3.305	8.155	8.240	8.286	8.354	8.433	8.479	8.504	8.518
	V	3.301	8.109	8.239	8.303	8.375	8.451	8.493	8.517	8.530
	Mean	3.305	8.101	8.221	8.278	8.350	8.431	8.476	8.502	8.517

is illustrated in Figure 3 where mean bulk densities of the 14 samples are plotted against mean compressional velocities at 10 kb. Also included in the figure are mean velocities and densities for the two Twin Sisters samples reported by Birch (1960) and Christensen (1966). The equation for the least square regression line of V_P on ρ at 10 kb for the 16 samples is $V_P = 4.70\,\rho - 7.04$. The scatter in the data points yields a correlation coefficient of 0.98. The equation at 10 kb for the least-square regression line of ρ on V_P is $\rho = 0.205\ V_P + 1.56$. Due to the lack of perfect linear correlation of the data, this latter solution has a slightly steeper slope than the regression line of V_P on ρ.

Ten of the samples shown in Figure 3 contain less than 5 percent serpentine and have mean densities ranging from 3.28 to 3.33. Mean velocities at different pressures for these 10 samples (30 cores) are given in Table 2. The velocities in Table 2 should be fairly representative for fresh dunite but are not necessarily the velocities for a pure olivine aggregate, since the samples included in this average contain up to 10 percent enstatite and chromite.

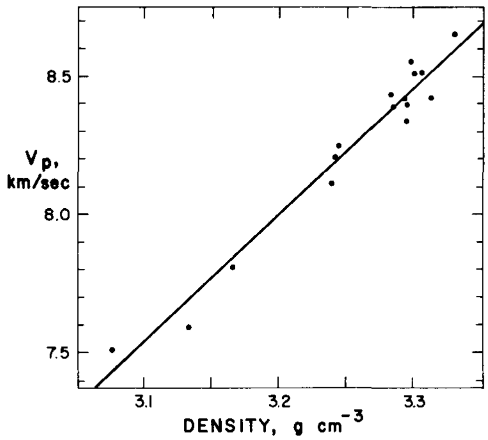

Figure 3. Velocity-density relations for Twin Sisters rocks at 10 kb.

Petrofabrics

Olivine orientations determined for each sample by standard universal stage techniques are shown in Figures 4 through 17. For several samples, the fabric diagrams were constructed from orientation data obtained from different portions of a sample. Olivine fabric was found to be relatively uniform throughout each dunite. The fabrics in Figures 4 through 17 are represented by equal area projections on the lower hemisphere. Corrections were not made for differences in the refractive indices of olivine and the 1.649 hemispheres. In all diagrams, the top is geographic north and the center is vertical.

DISCUSSION

Olivine Fabrics

The patterns of preferred olivine orientation in many of the dunites are similar. Samples TW-2, 4, 7, 8, 9, 10, 12, and 14 have mutually perpendicular maxima. In some cases, there are slight tendencies for partial girdling of one or more axes; however, positions of the maxima are well defined. Of particular significance for these samples are the orientations of the *b* crystallographic maxima which are close to horizontal and trend northeast-southwest to east-west. Olivine in these dunites occurs as irregular interlocking grains which have undergone only minor cataclasis.

The fabrics of samples TW-1, 3, 5, and 6 consist of olivine *a* crystallographic maxima perpendicular to *b* and *c* girdles. The girdles frequently contain well-defined maxima. Petrographic examination of these samples shows abundant cataclasis, usually in the form of irregular bands of granulated olivine. Bent exsolution lamellae and abundant kink bands within the enstatite of these specimens offer additional evidence of deformation. Sample TW-13, with a nearly random olivine orientation, shows extreme cataclasis. TW-11 has a rather unusual olivine fabric with an olivine *c* equal axis maxima and *a* and *b* girdles. Olivine *b* axes in samples TW-3, 5, 6, 11, and 13 also show tendencies to lie in a nearly horizontal orientation.

Fabric and Velocity Anisotropy

Birch (1960) reported large variations in compressional wave velocities with propaga-

TABLE 2. MEAN COMPRESSIONAL WAVE VELOCITIES FOR UNALTERED TWIN SISTERS DUNITE

Pressure, kb	0.2	1.0	2.0	4.0	6.0	8.0	10.0
Vp, km/sec	8.054	8.250	8.299	8.361	8.400	8.427	8.445

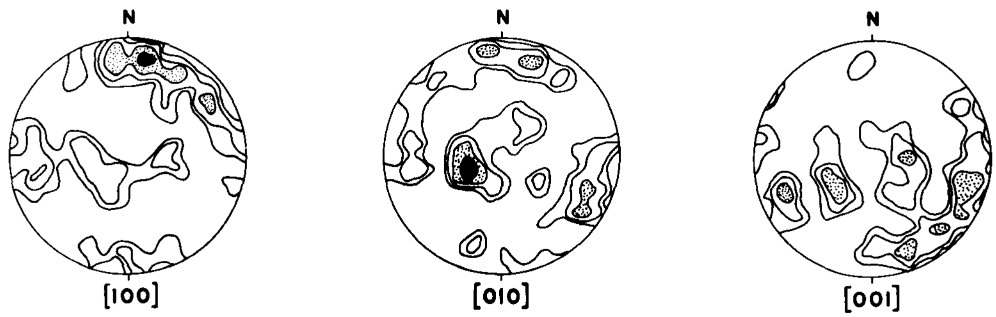

Figure 4. Preferred orientation of 100 *a*, *b*, and *c* axes of olivine in specimen TW-1. Contours 1, 2, 4, 8 percent per 1 percent area.

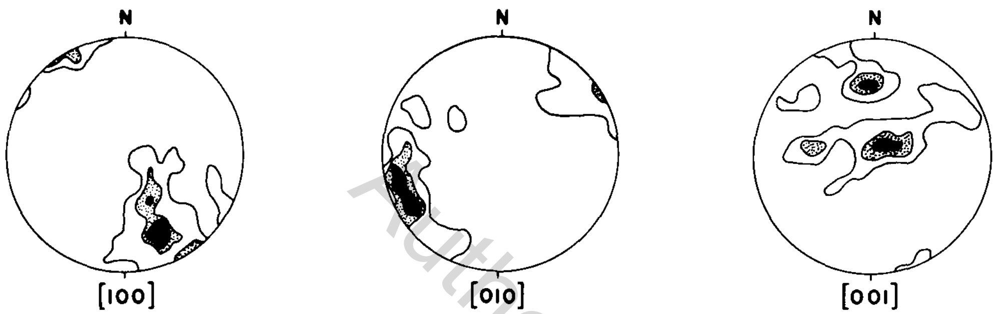

Figure 5. Preferred orientation of 50 *a*, *b*, and *c* axes of olivine in specimen TW-2. Contours 2, 6, 10 percent per 1 percent area.

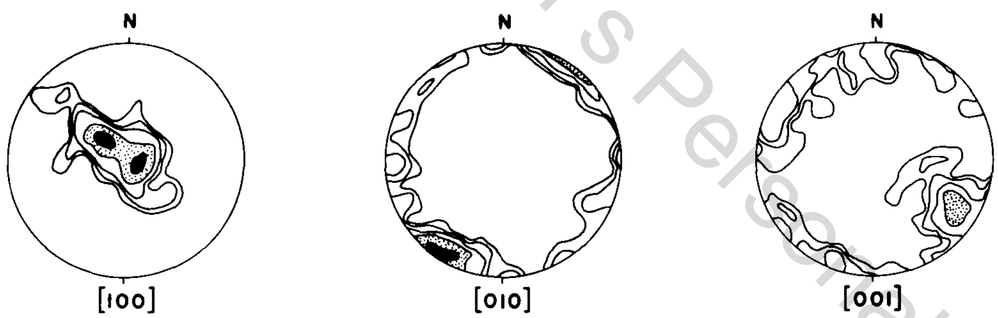

Figure 6. Preferred orientation of 100 *a*, *b*, and *c* axes of olivine in specimen TW-3. Contours 1, 2, 4, 8, 10 percent per 1 percent area.

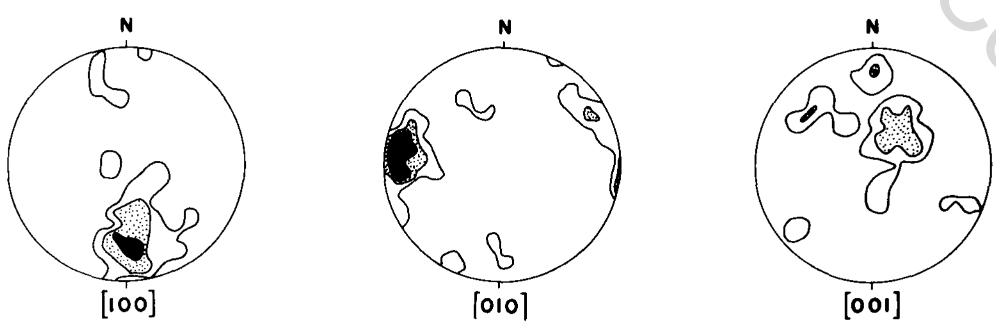

Figure 7. Preferred orientation of 50 *a*, *b*, and *c* axes of olivine in specimen TW-4. Contours 2, 6, 10 percent per 1 percent area.

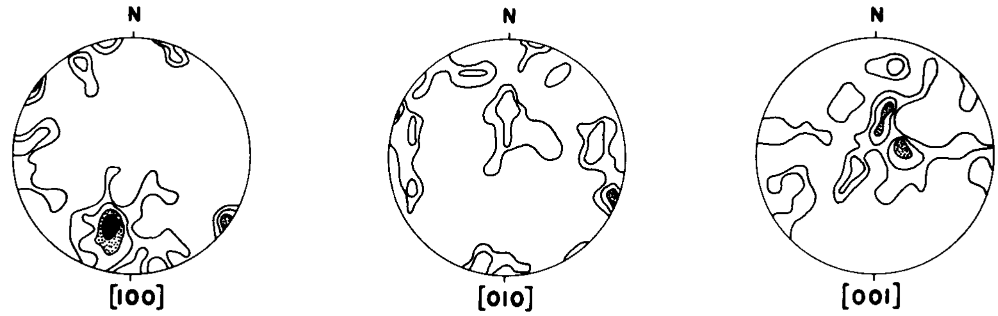

Figure 8. Preferred orientation of 50 *a*, *b*, and *c* axes of olivine in specimen TW-5. Contours 2, 4, 6, 8 percent per 1 percent area.

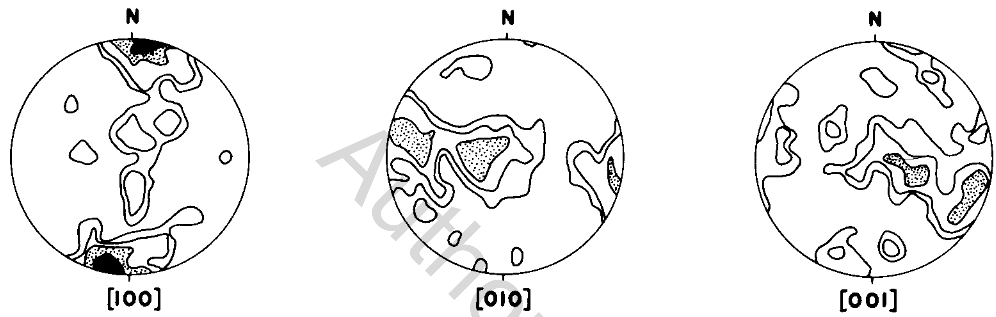

Figure 9. Preferred orientation of 100 *a*, *b*, and *c* axes of olivine in specimen TW-6. Contours 1, 2, 4, 8 percent per 1 percent area.

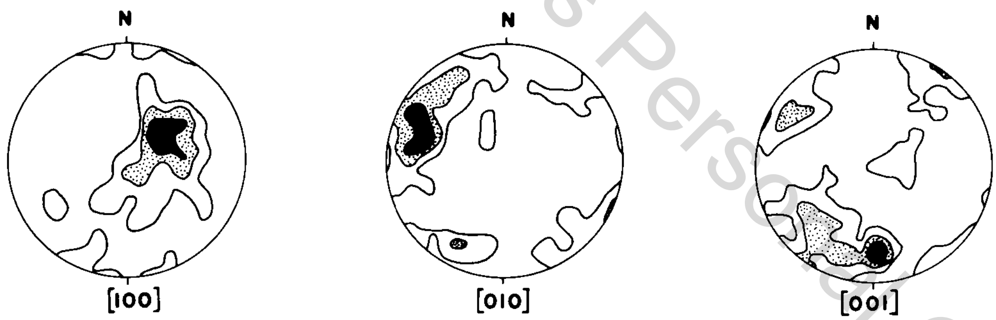

Figure 10. Preferred orientation of 100 *a*, *b*, and *c* axes of olivine in specimen TW-7. Contours 1, 4, 8 percent per 1 percent area.

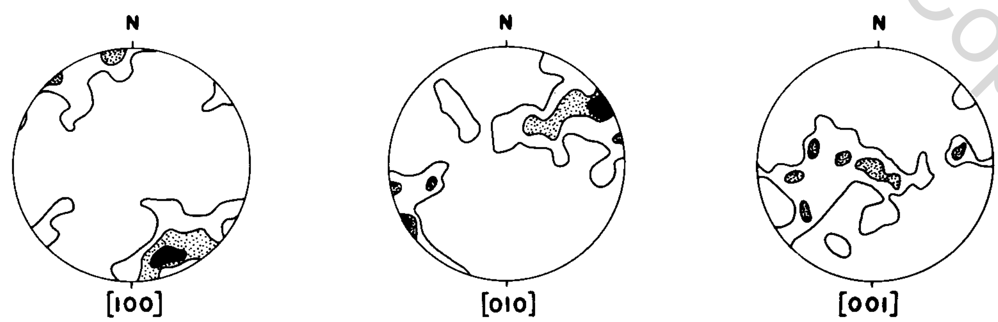

Figure 11. Preferred orientation of 50 *a*, *b*, and *c* axes of olivine in specimen TW-8. Contours 2, 6, 10 percent per 1 percent area.

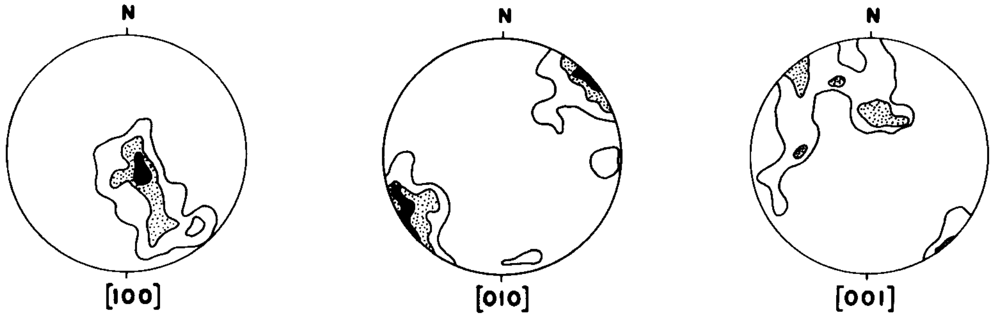

Figure 12. Preferred orientation of 50 *a*, *b*, and *c* axes of olivine in specimen TW-9. Contours 2, 6, 10 percent per 1 percent area.

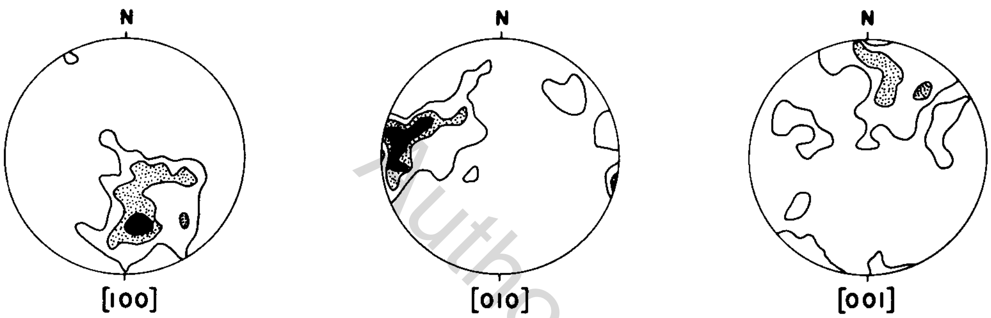

Figure 13. Preferred orientation of 50 *a*, *b*, and *c* axes of olivine in specimen TW-10. Contours 2, 6, 10 percent per 1 percent area.

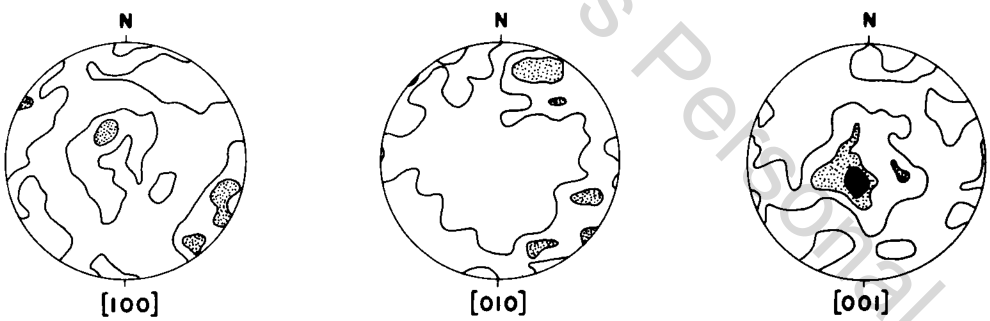

Figure 14. Preferred orientation of 100 *a*, *b*, and *c* axes of olivine in specimen TW-11. Contours 1, 4, 8 percent per 1 percent area.

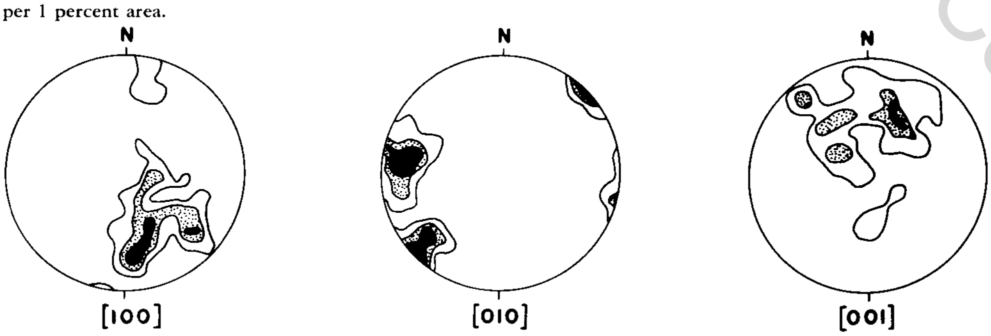

Figure 15. Preferred orientation of 50 *a*, *b*, and *c* axes of olivine in specimen TW-12. Contours 2, 6, 10 percent per 1 percent area.

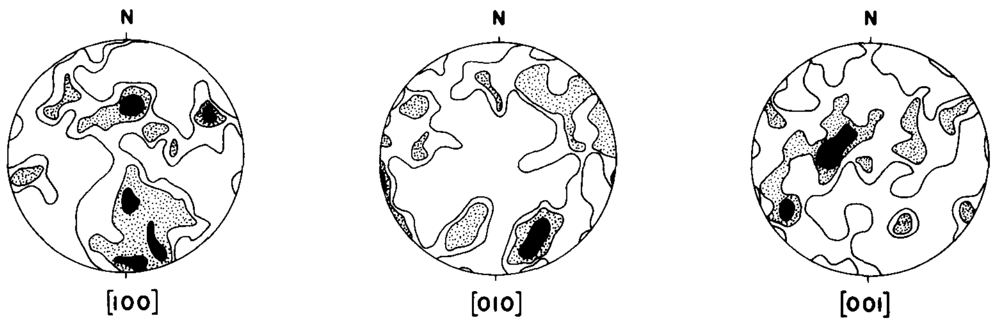

Figure 16. Preferred orientation of 100 *a*, *b*, and *c* axes of olivine in specimen TW-13. Contours 1, 2, 4 percent per 1 percent area.

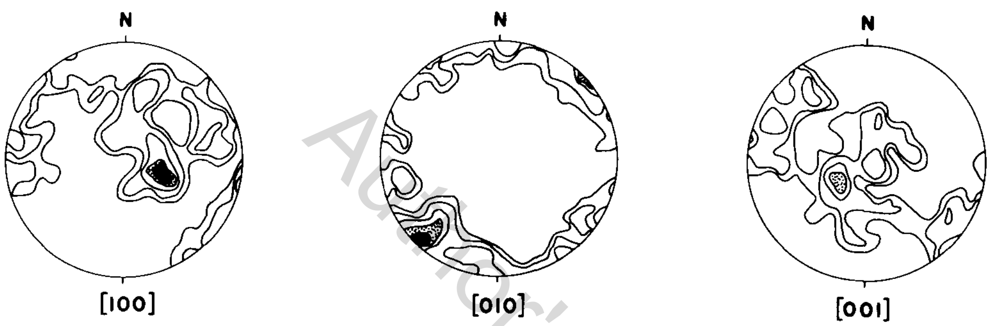

Figure 17. Preferred orientation of 100 *a*, *b*, and *c* axes of olivine in specimen TW-14. Contours 1, 2, 4, 6, 8 percent per 1 percent area.

tion direction for several olivine-rich rocks. For one specimen of Twin Sisters dunite, the anisotropy was found to be related to preferred olivine orientation (Birch, 1961). Later measurements by Christensen (1966) in a second sample of Twin Sisters dunite and a dunite from Addie, North Carolina, showed further correlation of fabric with velocity anisotropy. In these three samples, maximum velocities were found for propagation directions parallel to olivine *a* axis concentrations and minimum velocities correlated with propagation parallel to *b* axis concentrations. These results were found to be consistent with measurements by Verma (1960) in a single crystal of olivine ($Fo_{93}Fa_7$). Verma's compressional wave velocities parallel to the *a*, *b*, and *c* crystallographic axes are 9.87, 7.73, and 8.65 km/sec, respectively. Recent measurements by Kumazawa and Anderson (1969) for an olivine single crystal of similar composition are 9.887, 7.725, and 8.427 km/sec parallel to the *a*, *b*, and *c* axes.

For several samples (TW-2, 7, 10, 11, 13, and 14), the low-pressure velocities are inconsistent with measurements above a few kilobars. This most likely originates from grain boundary cracks which have an important influence on velocities at low pressures (Birch, 1961). Christensen (1965) demonstrated that correlation of velocity anisotropy and fabric in metamorphic rocks must be made at high pressures where grain boundary orientation effects have been minimized by crack closure.

The correlation of high-pressure velocities (Table 1) with fabric (Figs. 4 through 17) is generally excellent. Cores oriented with the direction of wave propagation parallel or close to parallel with *a* axes maxima (TW-1 N.-S., TW-2 N.-S., TW-3 V, TW-4 N.-S., TW-5 N.-S., TW-8 N.-S., TW-9 V, TW-14 V) have relatively high compressional wave velocities. An exception is the N.-S. core of TW-6 which has an intermediate velocity and is parallel to the concentration of *a* axes. For this rock, the vertical core shows a high velocity and high density, both of which may be related to less serpentinization. Samples TW-2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, and 14 have low velocities in an east-west direction that are related to *b* axes concentrations which trend horizontal and approximately east-west.

Several special fabrics and the apparent anisotropy resulting from these fabrics deserve attention. Samples TW-1, 3, and 5 have fabrics with strong olivine *a* axes maxima and *b* and *c* girdles. The patterns of anisotropy resulting from this orientation are characterized by higher velocities parallel to the *a* maxima and nearly equivalent lower velocities for propagation directions within the girdles. A similar velocity distribution was reported by Christensen (1966) for a sample of Addie, North Carolina, dunite. However, for this rock, the *b* axes formed a strong maximum and the *a* and *c* axes formed girdles. The anisotropy of this rock consisted of a low velocity parallel to the *b* axes concentration and high velocities for propagation within the girdles.

The fabric of sample TW-11 consists of a strong olivine *c* axis concentration and *a* and *c* girdles. The measurements reported in Table 1 for this rock suggest that rocks with this orientation pattern are nearly isotropic. Likewise, sample TW-14, which has weak olivine orientation and is also affected by moderate serpentinization, shows little variation of velocity with propagation direction.

Since the elastic properties of olivine are well known, several possibilities exist for quantitative approaches relating velocity in dunites to fabric. Birch (1961) presented a simple theory to obtain an approximation of the degree of olivine orientation from velocities which can be used to calculate velocities from fabric data. Birch assumed that compressional wave velocity for a particular propagation direction in dunite is related to the proportions of path length of the wave along the directions of the three crystallographic axes of olivine grains. If the proportions of path length are x, y, and z along the *a*, *b*, and *c* crystallographic directions, respectively, and $x + y + z = 1$, the corresponding velocity is given by $1/V = x/9.87 + y/7.73 + z/8.65$, where 9.87, 7.73, and 8.65 are velocities in km/sec along the olivine *a*, *b*, and *c* crystallographic axes (as reported by Verma, 1960). Estimates of the proportions of path length can be obtained from the fabric data by counting the number of crystallographic axes within a given angle of the wave propagation direction.

This technique has been applied with some success in calculating velocities for the serpentine free samples included in the present study. Calculated velocities using olivine axes falling within 30° of the propagation directions are within 5 percent of the measured velocities at 2 kb. The agreement is notably better for the samples in which olivine orientations have been determined for 100 grains. Additional fabric data might reduce the discrepancies still further. Also, some of the differences are most likely due to the influence of accessory minerals on the measured velocities.

Large-Scale Seismic Anisotropy

Ultramafic nodules commonly show strong preferred olivine orientation (see, for example, Ernst, 1935; Brothers, 1960; Brothers and Rodgers, 1969) and are therefore expected to be highly anisotropic to seismic wave propagation. The nodule fabrics are presumably often related to flow within the upper mantle. However, since the geographic orientation of olivine axes in nodules bears no relationship to their original orientation, the nodules offer no evidence as to whether olivine fabrics are consistent over large regions of the upper mantle.

Many alpine-type peridotites most likely originate from the upper mantle. As discussed earlier, the slablike geometry of the Twin Sisters body, its metamorphic texture, its probable emplacement as a relatively cold slab, and its favorable structural setting along the deep-seated Shuksan thrust strongly suggest an upper mantle origin. Evidence will be presented later for an upper mantle origin of many of the Twin Sisters fabrics; however, at present, the data in Table 1 and Figures 4 through 17 will be used to show that large-scale seismic anisotropy is present within the Twin Sisters Body.

The dominant feature of the Twin Sisters olivine fabric is the orientation of olivine *b* axes which are approximately horizontal and normal to the elongation of the body. Olivine *a* and *c* axes maxima tend to lie in a vertical plane normal to the *b* axes maxima. The orientation of these latter maxima vary from vertical to horizontal. This is supported by the data in Table 1 which give mean compressional wave velocities at 10 kb of 8.30, 7.99, and 8.37 km/sec for north-south, east-west, and vertical propagation directions, respectively.

Velocities at 10 kb versus direction are shown in Figure 18. In this figure, velocities of the lower-density samples have been corrected for serpentine content by using the velocity-density relationship given in Figure 3. The data in Figure 18 clearly illustrate the low east-west velocities for the Twin Sisters dunite and strongly suggest that the entire Twin Sisters body is anisotropic to seismic wave propagation. Mean velocities corrected for serpentine at 10 kb are 8.60 km/sec north-south, 8.29 km/sec east-west and 8.67 km/sec vertical. The higher velocities in the vertical direction suggest a rather weak tendency for the olivine *a* axes to assume a vertical orientation.

Fabric and Emplacement of the Twin Sisters Dunite

Ave'Lallement and Carter (1970) recently presented important data on olivine textures produced by experimental syntectonic recrystallization. In these experiments, olivine was recrystallized at confining pressures from 5 to 30 kb, temperatures from 950°C to 1350°C and strain rates from 10^{-3} to 10^{-8}/sec. Under these conditions, olivine *b* axes maxima parallel σ_1, and olivine *a* and *c* axes form girdles in the $\sigma_2 = \sigma_3$ plane. When $\sigma_2 \neq \sigma_3$, olivine *a* axes orient parallel to σ_3. Ave'Lallemant and Carter (1970) estimated that under strain rates expected in the upper mantle, this fabric produced by recrystallization forms at temperatures greater than 500°C. At slightly lower temperatures, olivine deforms by plastic flow (Ave'Lallemant and Carter, 1970). Several slip systems important in plastic flow have been produced experimentally (Raleigh, 1968; Carter and Ave'Lallemant, 1970). The different slip systems have been shown to be related to both temperature and strain rate.

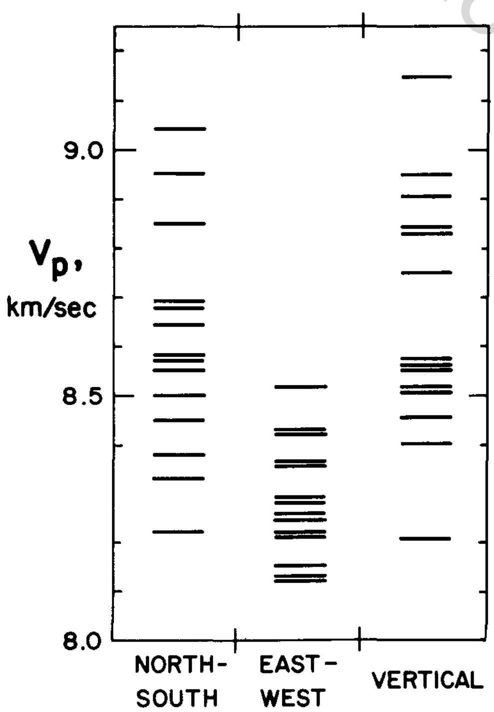

Figure 18. Compressional wave velocities at 10 kb versus direction.

Textures of several samples of Twin Sisters dunite are similar to olivine textures produced by recrystallization. The fabrics of these samples tend to show strong mutually perpendicular maxima of all three olivine axes. Other samples of Twin Sisters dunite showing abundant kink bands, abundant cataclasis, and undulatory extinction of both olivine and enstatite appear to have their fabrics modified by plastic flow and granulation. These latter examples tend to have either weak fabrics or strong olivine *a* maxima and *b* and *c* girdles.

The olivine fabrics which have originated by recrystallization appear to have an upper mantle origin, because recrystallization in the lower crust accompanying the rise of the dunite body along the root of the Shuksan thrust would have produced a much different olivine orientation than that observed. This is illustrated schematically in the east-west cross section of Figure 19A. The shear sense along the thrust and the principal stresses $_1$ and $_3$ are shown in the eastern side of the diagram as well as the olivine fabric consistent with the experimental results of Ave'Lallemant and Carter (1970). Late folding of the Shuksan plate after emplacement of the Twin Sisters dunite would produce olivine orientation with *b* axes nearly vertical and *a* axes close to horizontal in an east-west plane (Fig. 19A).

Ave'Lallemant and Carter (1970) have presented two models of flow in the upper mantle and corresponding olivine orientations for each model. The two models differ primarily in the mechanism which is responsible for plate motion. In the first model, plate motions result from drag by creep of convecting mantle below the plates, whereas the second model attributes plate motion to push by injection of magma near oceanic ridges or pull from sinking plates in the vicinity of trenches (or both of these factors).

The over-all olivine fabric of the Twin Sisters dunite may be used to test these two models. Since the continental margin was to the west and Cretaceous thrusting in the region was from east to west, plate motion during the time of emplacement of the Twin Sisters dunite was most likely from east to west. The resulting shear sense within the plate is illustrated in Figure 19B, assuming that the plate was carried below by convective flow (Model 1). The resulting olivine fabric corresponding to this shear sense is shown in Figure 19B. The final olivine orientation after folding of the thrust plate is illustrated in the left side of Figure 19B, assuming that the mantle fabric remained unmodified during emplacement along the Shuksan thrust.

This model is certainly subject to much speculation; however, the predicted orientation is remarkably similar to the fabric observed in the Twin Sisters dunite. As has been discussed previously, fabrics which deviate from this model most likely originated by plastic flow and cataclasis which accompanied emplacement along the thrust. The tendency for both olivine

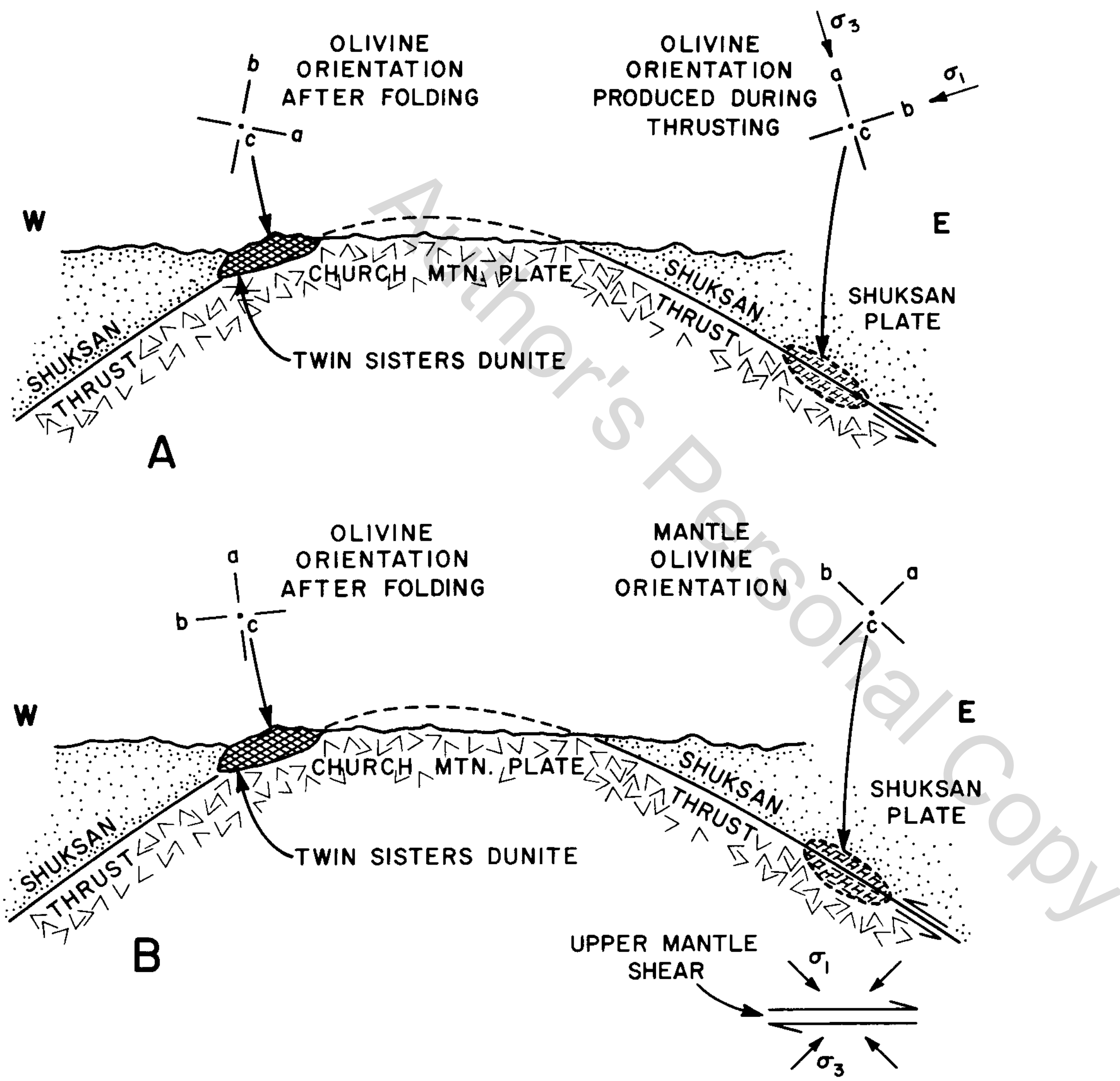

Figure 19. Models for the generation of olivine fabric in the Twin Sisters dunite (see text).

a and *c* axes to lie in girdles parallel to a north-south vertical plane suggests that $\sigma_2 \simeq \sigma_3$ in the upper mantle.

The second model for upper mantle flow has an opposite direction of shear sense (Ave'Lallemant and Carter, 1970), and therefore olivine orientation would be opposite to that observed in the Twin Sisters body. This suggests that plate motion in the upper mantle is due to drag from below the plates, rather than rigid translation resulting from forces in the vicinities of ocean ridges and trenches.

ACKNOWLEDGMENTS

I wish to thank R. Conway, M. Mulcahey, and K. V. Campbell for technical assistance. R. L. Gresens and Peter Misch offered many helpful suggestions for improvement of the manuscript. Financial support was provided by National Science Foundation Grants GA-1461 and GA-20317.

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MANUSCRIPT RECEIVED BY THE SOCIETY OCTOBER 28, 1970

PRINTED IN U.S.A.