Elastic Moduli and Anisotropy of Dunite to 10 Kilobars

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Longitudinal and transverse wave velocities are reported for several directions at pressures to 10 kb in two samples of dunite from the Twin Sisters peaks, Washington. For both dunites, elastic-wave propagation is controlled to a large extent by olivine fabric. Dunite A, which has a strong concentration of olivine *a* crystallographic axes and girdles of *b* and *c* axes, is uniaxial in elastic properties. The longitudinal wave velocity at 10 kb for propagation parallel to the olivine *a* axes maximum is 8.76 km/sec. For propagation normal to the *a* axes maximum, longitudinal wave velocities are low ($V_p = 7.98$ km/sec at 10 kb) and two transverse waves ($V_s = 4.41$ and 4.69 km/sec at 10 kb) are clearly transmitted through the rock. Dunite B, with strong concentrations of all three olivine crystallographic axes, is similar in elastic properties to orthorhombic crystals with a high longitudinal wave velocity (9.15 km/sec at 10 kb) along the olivine *a* axes maximum and a low longitudinal wave velocity (7.83 km/sec at 10 kb) along the olivine *b* axes concentration. Elastic stiffnesses and compliances were computed from the velocities, and the physical properties of isotropic aggregates of the two dunites were calculated using the Voigt and Reuss averaging techniques. Primarily because of the presence of accessory minerals in the dunites, the Voigt and Reuss velocities are lower than values computed from olivine single-crystal data. The high pressure gradient ($\partial V_p/\partial P =$ 17.0 km sec^{-1} mb^{-1}) observed for the longitudinal velocity of dunite B at 8 kb is interpreted as being due to the effect of grain boundary cracks.

Several papers [*Hess*, 1964; *Raitt et al.*, 1969; *Meyer et al.*, 1969; *Keen and Tramontini*, 1970] have presented evidence from seismic refraction studies that parts of the oceanic upper mantle are anisotropic to compressional wave propagation. If this anisotropy is the result of preferred mineral orientation, seismic refraction data may eventually provide important information on mineral fabric in the upper mantle, which in turn may lead to a better understanding of flow mechanisms and flow directions associated with plate motion. Since olivine is generally believed to be a major constituent of the upper mantle, it is of importance to understand the relationship between seismic-wave propagation and fabric in dunite.

Very little experimental data are available on seismic anisotropy of dunites at high pressures. *Birch* [1960, 1961] was the first to find that longitudinal wave velocities vary significantly with propagation direction in dunites. In Birch's study, measurements were made in three mutually perpendicular directions. Although fabric diagrams were not given, *Birch* [1961] found that the fast direction in a specimen of Twin Sisters dunite was parallel to a strong concentration of olivine *a* axes. *Christensen* [1966*b*] reported longitudinal wave velocities in three directions for a second sample of Twin Sisters dunite and in seven directions for a dunite from Addie, North Carolina. Fabric diagrams for both samples demonstrated that longitudinal wave anisotropy at pressures above a few kilobars was clearly related to olivine fabric.

Christensen [1966*a*] found that transverse wave velocities in metamorphic rocks vary with propagation direction and displacement direction. Although transverse wave velocities have been measured at pressures to 10 kb for different propagation directions in dunite [*Simmons*, 1964; *Christensen*, 1966*b*], the relationships between transverse wave velocities and olivine orientation for different displacement directions along a given propagation direction have not yet been investigated.

In addition to the experimental studies of anisotropic rock elasticity, several papers have attempted to relate preferred mineral orientation in rocks and the elasticity of their constituent minerals to a predicted pattern of rock

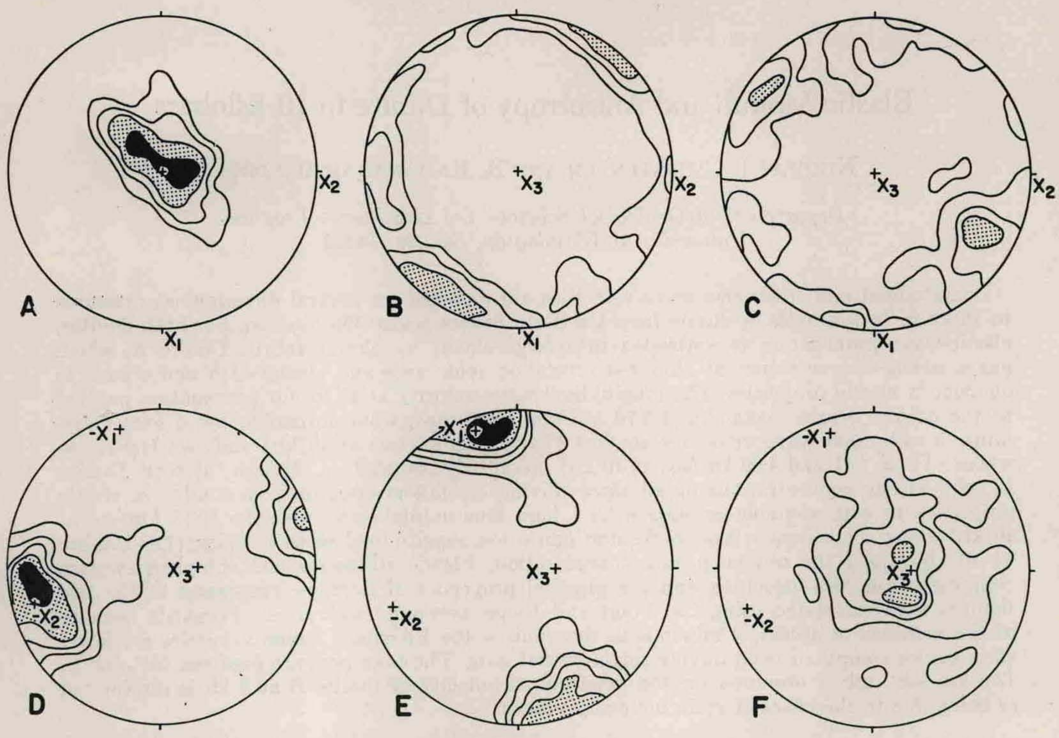

Fig. 1. Orientation diagrams for 200 grains of olivine in dunite A (*A–C*) and dunite B (*D–F*): (*A*) *a* axes, contours 10%, 5%, 3%, and 1% per 1% area; (*B*) *b* axes and (*C*) *c* axes, contours 5%, 3%, and 1% per 1% area; (*D*) *b* axes and (*E*) *a* axes, contours 10%, 7%, 5%, 3%, and 1% per 1% area; (*F*) *c* axes, contours 7%, 5%, 3%, and 1% per 1% area.

anisotropy. *Kumazawa* [1964] presented a stimulating discussion of the effect of grain boundaries and preferred mineral orientation on the elastic properties of rocks and proposed theoretical models for the elastic anisotropy of dunites with different olivine orientation patterns. *Christensen and Crosson* [1968] summarized available fabric data of dunites and peridotites and postulated that, depending on the details of their fabric, the elasticity of common olivine-rich rocks is similar to either hexagonal or orthorhombic crystals. *Alexandrov et al.* [1969] have described a systematic technique for studying the complete elastic properties of rocks and have reported elastic moduli for several anisotropic rocks at atmospheric pressure.

We have studied in detail the elastic anisotropy

TABLE 1. Modal Analyses (Percentages by Volume)

Mineral	Dunite A	Dunite B
Olivine	83.1	96.3
Enstatite	2.1	0.9
Serpentine	12.1	0.2
Chromite + Magnetite	2.7	2.6

TABLE 2. Chemical Analyses (Percentages by Weight)

Component	Dunite A	Dunite B
SiO_2	40.8	40.5
Al_2O_3	0.26	0.78
TiO_2	0.25	0.11
FeO	7.80	8.34
Fe_2O_3	0.92	0.53
MgO	49.1	48.5
CaO	0.02	0.13
K_2O	0.01	0.07
Na_2O	0.20	1.30
MnO	0.03	0.15
Cr_2O_3	0.19	0.62
H_2O	1.30	0.16
Total	100.67	101.19