ELSEVIER

Tectonophysics 355 (2002) 163–170

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Continental mantle seismic anisotropy: a new look at the Twin Sisters massif

Nikolas I. Christensen*

Department of Geology and Geophysics, University of Wisconsin-Madison, Lewis G. Weeks Hall, 1215 Dayton Street, Madison, WI, 53706-1692, USA

Received 13 November 2000; accepted 7 June 2001

Abstract

Recent interpretations of upper continental mantle seismic anisotropy observations have often relied on fabric measurements and calculated anisotropies of upper mantle xenoliths. Seismic ray paths of P and S waves, which provide information on azimuthal compressional wave anisotropy and shear wave splitting, are tens to hundreds of kilometers, whereas, xenoliths are usually only a few centimeters in diameter. To place better constraints on field-based anisotropy observations and to evaluate anisotropy information provided by xenoliths, it is important to examine anisotropy in large ultramafic massifs which have originated in the upper mantle. One such massif is the Twin Sisters Range located in the western portion of the North Cascades of Washington State, USA. The Twin Sisters massif, a slab of unaltered dunite, is 16 km in length, 6 km in width and 3 km thick. Exposed along its south and west sides are mafic granulite facies rocks, which likely represent lower continental crustal fragments. The ultramafic rocks are porphyroclastic in texture, consisting of strained, flattened porphyroclasts of olivine and enstatite and strain-free olivine mosaics. Olivine fabrics are typical of those formed at high temperatures and low strain rates. Petrofabrics and calculated anisotropies of individual samples vary throughout the massif, however, overall anisotropy of the body is significant, with maximum P and S waves anisotropies of 5.4% and 3.9%, respectively. The maximum delay time for split shear waves traveling through a 100-km-thick slab is 0.8 s and two directions of shear wave singularity are observed. The directions of maximum shear wave splitting and shear wave singularities do not coincide with the directions of maximum and minimum compressional wave velocity. In general, individual hand samples show significantly higher anisotropy than the overall anisotropy of the massif. It is concluded that simple averages of xenolith anisotropies are unreliable for use in the interpretation of field anisotropy observations.

Keywords: Anisotropy; Peridotite; Upper mantle; Petrofabrics; Olivine; Velocity

1. Introduction

During the past decade, much research has been devoted to studies of upper continental mantle seismic anisotropy. Mantle anisotropy originates from lattice-preferred orientations of minerals. The major minerals of the upper mantle, olivine and pyroxene are often tabular in shape, which produces a rock foliation similar to that observed in crustal high-grade metamorphic rocks such as mica schists. Upper mantle anisotropy observations thus provide information on the orientation of foliation, which is related to the deformational history of the upper mantle.

* Fax: +1-608-262-0693.
E-mail address: chris@geology.wisc.edu (N.I. Christensen).

0040-1951/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0040-1951(02)00139-7

To interpret field observations of azimuthal Pn anisotropy and shear wave splitting, it is necessary to have information on the magnitudes and symmetries of seismic anisotropies of mantle rocks. Mantle-derived xenoliths have been used for laboratory-based anisotropy measurements at elevated pressures and anisotropy calculations from petrofabric analyses (for a review of previous xenolith studies, see Soedjatmiko and Christensen, 2000). Problems inherent to xenolith studies originate from the small size of xenoliths and possible alteration and fabric modifications originating from their rapid and often violent ascent to the Earth's surface. It is thus desirable to study seismic anisotropy in large, tectonically emplaced slabs of mantle rock, which give information on seismic anisotropy on a much larger scale.

The Twin Sisters ultramafic massif (Fig. 1) occurs as a rugged, glaciated mountain range 16 km in length and 6 km in width, located in the western portion of the North Cascades of Washington State, USA. This

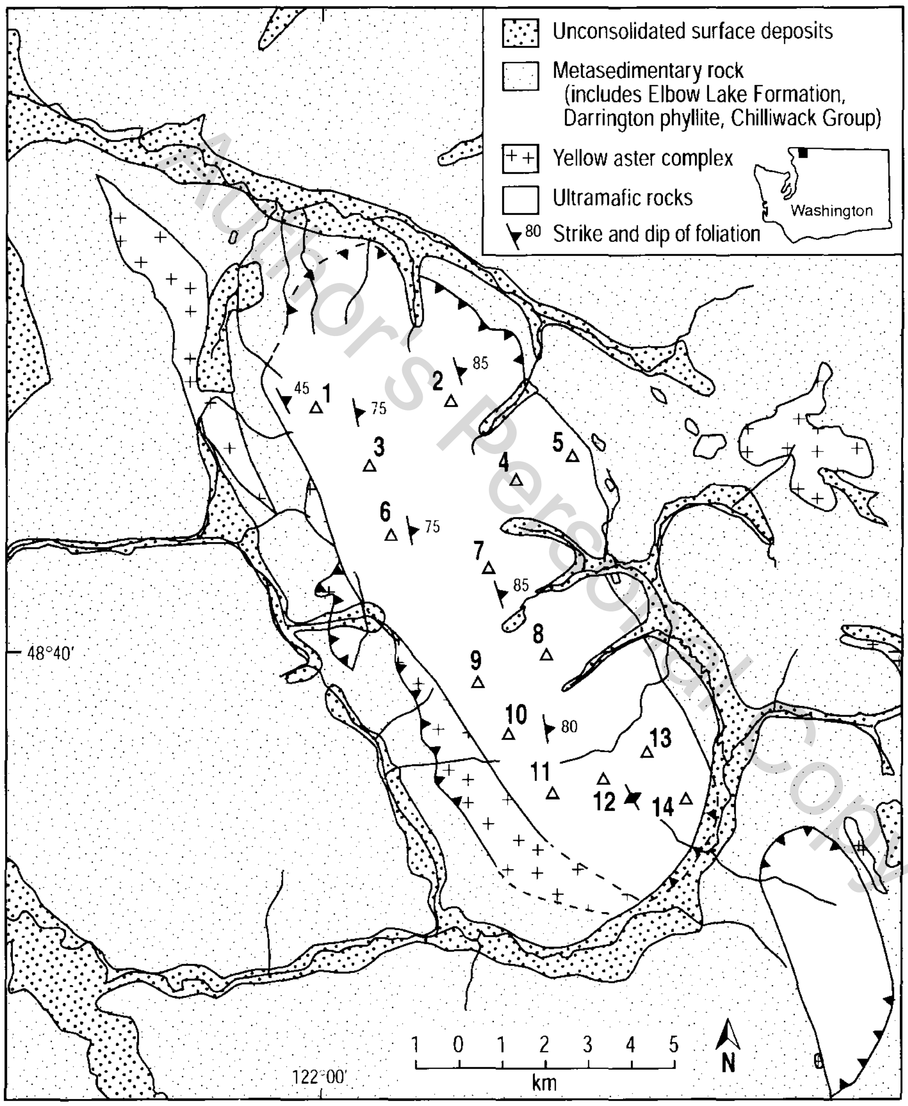

Fig. 1. Map of the Twin Sisters region showing locations of the dunite and lower crustal Yellow Astor Complex (modified from Brown et al., 1987). Sample locations are shown as triangles.

massif is one of the world's best exposed and least altered surface exposure of upper mantle rock. The ultramafic rocks which form the Twin Sisters massif occur within a mélange consisting of a variety of rocks with continental and oceanic affinities. High-grade metamorphic rocks, termed the Yellow Astor Complex (Misch, 1966), occur in contact with the mantle rocks along the southern and western sides of the Twin Sisters massif and as large blocks to the east. The majority of the Yellow Astor rocks are amphibolite facies grade of both igneous and sedimentary origin. Clinopyroxene–plagioclase–quartz gneisses are also common in the vicinity of the Twin Sisters massif. Misch (1966) reports similar hypersthene-bearing gneisses further east, supporting granulite facies metamorphism for portions of the Yellow Astor Complex. Although the exact structural relationships between the Twin Sisters massif and the Yellow Astor Complex are uncertain, their close association suggests a continental origin for the ultramafic rocks of the Twin Sisters massif.

The purposes of this paper are to examine in detail the seismic anisotropy of the Twin Sisters massif and to compare its anisotropy with individual hand samples and mantle anisotropy observations.

2. Internal structure, petrology and petrofabrics

The Twin Sisters massif consists largely of dunite, with minor harzburgite. Chromite layering is common and pyroxenite layers are also locally present. The layering generally parallels dunite foliations defined by olivine flattening, trends NNW–SSE, parallel to the long axis of the massif (Fig. 1), and is usually steeply dipping. There is some indication of isoclinal folding in the massif, evidenced by isolated fold hinges of chromite.

Olivine, Fo $_{90-92}$, is the major constituent of the massif. Grain size ranges from 0.01 mm to over 2 cm. Some samples show a bimodal olivine size distribution, with large deformed porphyroclasts, ranging in size from 20 to 5 mm, and smaller strain-free neoblasts, which are less than 5 mm. Other samples have a continuous range in grain sizes. Porphyroclasts have undulose extinction, kink bands and deformation lamellae. Aspect ratios of flattened olivine grains reach values as high as 5:1. Kink band boundaries tend to be at high angles to the foliation. Typical thin-section photographs of the dunite are illustrated in an early paper by Ragan (1963).

Enstatite is a common accessory mineral, but rarely forms more than 5% of the dunite. It occurs as large, deformed porphyroclasts. Cleavage traces and clinopyroxene exsolution lamellae are often oriented subparallel to the olivine elongation. Crosscutting veins of bright green chrome diopside are locally present. Chromite is ubiquitous and occurs in bands and as a common accessory mineral in the dunite. There is no chromite-preferred direction of flattening or stretching of the grains that define a lineation. Throughout the interior of the massif, the dunites show remarkably little alteration. Serpentine, when present, occurs as veinlets which crosscut grain boundaries of olivine and pyroxene. Local concentrations of serpentine occur along the margin of the massif and in the interior shear zones which trend approximately north–south (Ragan, 1963).

Olivine petrofabric analyses reveal a fairly consistent orientation of olivine within the core of the body (Christensen, 1971a). The dominant feature is the orientation of olivine *b* crystallographic axes, which are approximately horizontal and normal to the elongation of the body. Olivine *a* and *c* axes maxima lie in a vertical plane normal to the *b* axes maxima. The fabrics throughout the massif likely originated during recrystallization and intracrystalline glide on the {0k*l*} [100] and (010) [100] slip systems (Christensen, 1971a). These fabrics originated in a high temperature, low strain rate upper mantle environment (Carter and AvéLallemant, 1970; Nicolas et al., 1973).

In the previous Twin Sisters petrofabric and anisotropy study, 100 olivine grains were oriented for seven locations and 50 olivine grains were oriented for seven locations. Using the original field-oriented thin sections, an additional 50 grains have been oriented with a five axis universal stage, such that 100 grains have been measured for each of the 14 locations shown in Fig. 1. The additional data have not revealed any major changes in symmetry or maxima locations in the previous fabric diagrams, however, they have better defined some maxima.

Olivine orientation composite fabric diagrams determined from the 1400 olivine grain orientations are shown in Fig. 2. The fabrics are represented with Schmidt contours and equal area projections on the

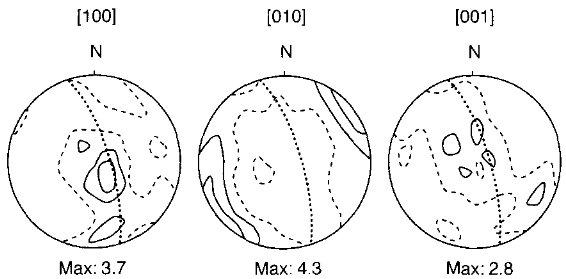

Fig. 2. Olivine fabrics plotted on lower hemisphere projections based on a total of 1400 olivine orientations from the 14 sample locations shown in Fig. 1. Fabrics are contoured at 1% intervals with the lowest contours (1%) shown as dashed lines. Average foliation orientation is shown as a great circle.

lower hemisphere. The tops of the contour diagrams are geographic north and the centers are vertical. The overall olivine orientation of the Twin Sisters massif shows a strong concentration of olivine *b* axes that are horizontal and approximately normal to the elongation of the body (Fig. 1) and dunite foliations. The olivine crystallographic *c* and *a* axes form incomplete girdles within the foliation and normal to the *b* axes concentration. A pronounced olivine *a* axes maximum which dips steeply to the south, occurs within the *a* axes girdle.

3. Seismic anisotropy

In a previous study of Twin Sisters anisotropy, Christensen (1971a) measured the compressional wave velocities to hydrostatic confining pressures of 1 GPa (equivalent to a depth of approximately 35 km) for three cores cut from field-oriented rock samples collected from each of the 14 locations shown in Fig. 1. One core was taken with a vertical field orientation and the other two were oriented in a horizontal plane with their axes at north–south and east–west. The measured velocities showed a common pattern of anisotropy throughout the massif in which slow velocities were measured from horizontal east–west cores, consistent with the SW–NE olivine *b* axes concentrations of Fig. 2. Compressional wave velocities for vertical propagation were, on average, the highest of the three directions of measurement.

This anisotropy study was limited to laboratory measurements of compressional wave velocities, since early upper mantle anisotropy observations were limited to Pn studies in oceanic upper mantle (e.g., Hess, 1964; Morris et al., 1969). Shear wave splitting

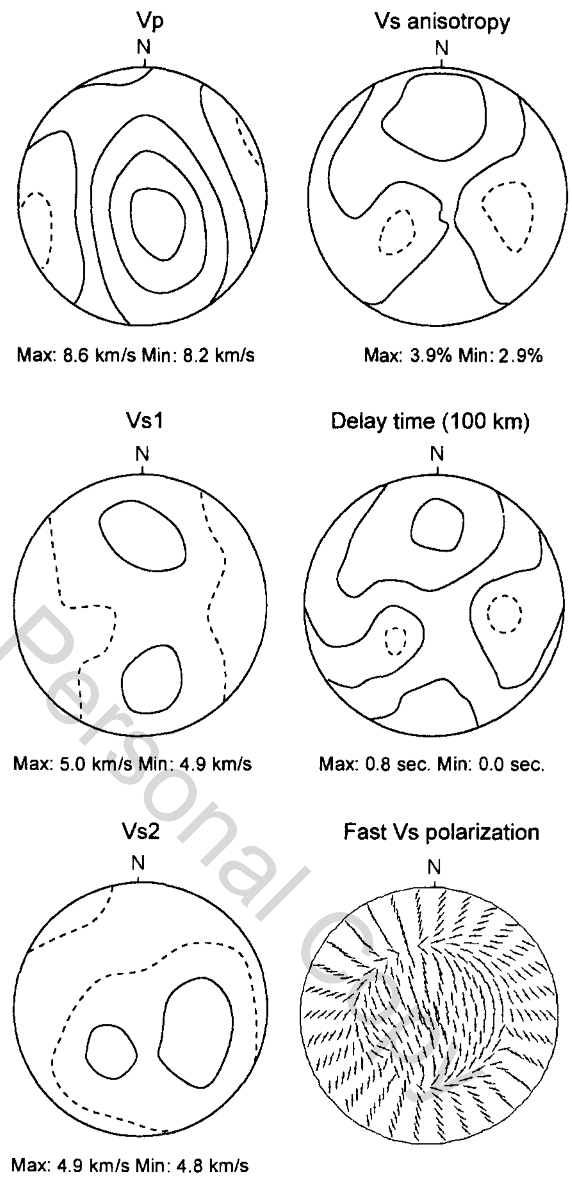

Fig. 3. Twin Sisters compressional wave velocity (V_p, km s^{-1}), fast shear wave velocity (V_{s1}, km s^{-1}), slow shear wave velocity (V_{s2}, km s^{-1}), shear wave anisotropy (%), delay time for a 100-km slab (s) and vibration directions for the fast shear wave plotted on lower hemisphere projections. Contour intervals are 0.1 km s^{-1} for V_p, 0.05 km s^{-1} for V_s, 1% for V_s anisotropy and 0.2 s for 100-km slab delay time. Minimum contours are shown as dashed lines.

Table 1
Compressional (V_p) anisotropies, shear (V_s) anisotropies and splitting delay times

Sample	V_p anisotropy (%)	Maximum splitting direction		Minimum splitting direction	
		V_s anisotropy (%)	Delay time (s) 100-km slab	V_s anisotropy (%)	Delay time (s) 100-km slab
TW-1	5.5	5.1	1.10	0.2	0.05
TW-2	12.5	8.9	1.73	0.6	0.14
TW-3	15.1	11.0	2.03	0.6	0.14
TW-4	13.0	10.1	1.87	0.2	0.05
TW-5	6.1	4.9	1.08	0.2	0.05
TW-6	10.5	7.8	1.55	0.4	0.09
TW-7	9.9	8.6	1.67	0.2	0.05
TW-8	9.2	8.1	1.60	0.2	0.05
TW-9	13.4	9.9	1.83	0.4	0.09
TW-10	11.9	8.1	1.60	0.4	0.09
TW-11	4.1	3.7	0.85	0.0	0.00
TW-12	12.9	8.3	1.65	0.0	0.00
TW-13	3.7	3.7	0.85	0.2	0.05
TW-14	8.9	7.8	1.55	0.2	0.05
Sample average	9.8	7.6	1.50	0.3	0.06
Massif	5.4	3.9	0.90	0.0	0.00

had not been recognized from field observations, although early laboratory studies (Christensen, 1966, 1971b) had reported splitting in several crustal and mantle rocks and correlated the splitting with lattice-preferred orientations of highly anisotropic silicate minerals such as mica, amphibole, pyroxene and olivine. Subsequent early findings of shear wave splitting of upper mantle origin (e.g., Ando et al., 1983; Vinnik et al., 1984; Silver and Chan, 1988) and more recent investigations (e.g., Ozalaybey and Savage, 1995; Savage, 1999) have provided incentives for additional laboratory-based studies of shear wave anisotropies in mantle rocks.

Shear and compressional wave anisotropies have been calculated at a confining pressure of 1 GPa and a temperature of 500 °C for individual samples and the complete massif using the computer program of Crosson and Lin (1971). From the single crystal elastic constants of olivine, their temperature and pressure derivatives (Kumazawa and Anderson, 1971) and the universal stage orientation data, the program calculates the contribution of each mineral grain 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. Several studies (Crosson and Lin, 1971; Kern et al., 1996; Long and Christensen, 2000) have found good agreement between the calculated- and laboratory-measured anisotropies.

The Voigt–Reuss–Hill calculations for the Twin Sisters massif based on 1400 olivine orientations from the 14 sample locations shown in Fig. 1 and the composite fabrics diagrams of Fig. 2 are shown in Fig. 3 in lower hemisphere projections. Contoured diagrams are shown for compressional wave velocity (V_p), the maximum shear wave velocity (V_{s1}), the minimum shear wave velocity (V_{s2}), shear wave anisotropy (V_s anisotropy) defined as the velocity difference in the split shear waves expressed as a percent of the mean shear wave velocity, the shear wave delay time in seconds for a 100-km-thick section and vibration directions for the fast shear wave.

In Table 1, anisotropies are compared for each sample with sample averages and the overall anisotropy of the Twin Sisters massif. The significance of these results will be discussed in Section 4.

4. Discussion and conclusions

Upper mantle xenolith anisotropies have often been used to interpret continental mantle shear wave splitting observations (e.g., Mainprice and Silver, 1993; Ji et al., 1994; Ben Ismail and Mainprice,

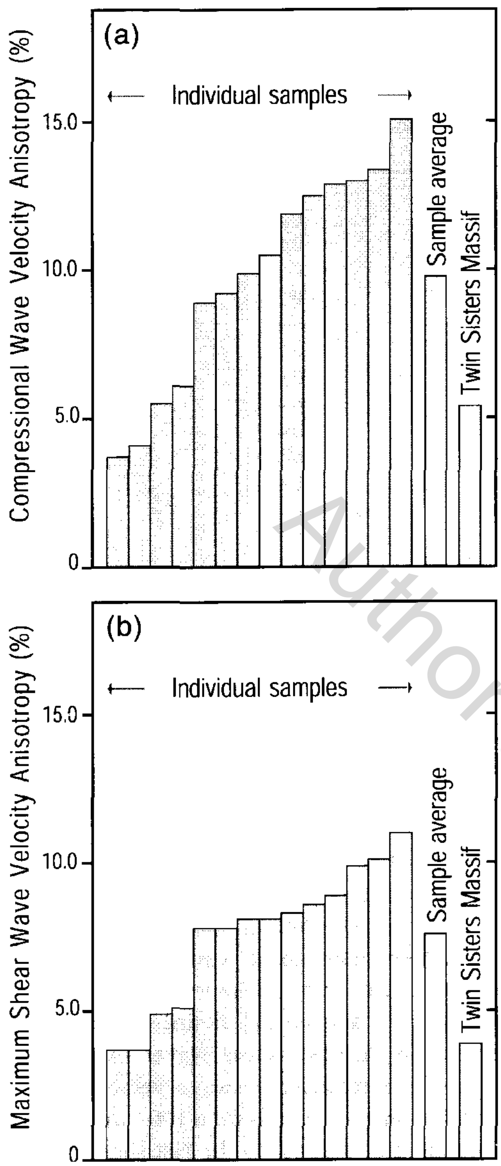

Fig. 4. Calculated compressional and shear anisotropies for individual samples compared with Twin Sisters massif anisotropies. Note that the sample averages are significantly higher than the massif anisotropies.

1998; Soedjatmiko and Christensen, 2000). In these studies, averages of suites of hand samples have often been assumed to represent average mantle anisotropy. Examinations of Table 1 and Fig. 4 show that sample averages give both compressional and shear wave anisotropies significantly higher than actual anisotropies of larger volumes of mantle rock. This is because averages of individual samples assume that olivine maxima of each sample are oriented parallel to one another, which is not the case in situ. This is analogous to observations of foliations in high-grade metamorphic terranes, which deviate significantly from one another on outcrop scale but show regional patterns.

Pn anisotropy of the upper mantle averages 4% (Smith and Ekstrom, 1999). Since Pn anisotropy observations are two-dimensional, their comparisons with Twin Sisters V_p anisotropy need to be based on calculated anisotropies in planar sections through the contoured V_p diagram of Fig. 3. The field orientation of the massif is likely different from its in situ mantle orientation, however, anisotropy in a horizontal plane is 3.7% (plane A, Fig. 5a) which is in good agreement with average field-based observations. Anisotropy within the average foliation of the massif (plane B, Fig. 5a) is 3.5%, also in reasonable agreement with the average continental upper mantle Pn anisotropy. The plane with maximum anisotropy (5.4%) strikes approximately N75°E and dips steeply to the south (plane C, Fig. 5a). This plane contains the slow olivine *b* axes maximum and the fast olivine *a* axes maximum. Two planes through the massif show no or minimal P anisotropy (planes D and E, Fig. 5a), illustrating that based on Pn observations, a highly anisotropic mantle can appear isotopic.

Shear wave splitting in mantle ultramafic rocks varies significantly with propagation direction (e.g., Kern, 1993). Shear wave splitting for four propagation

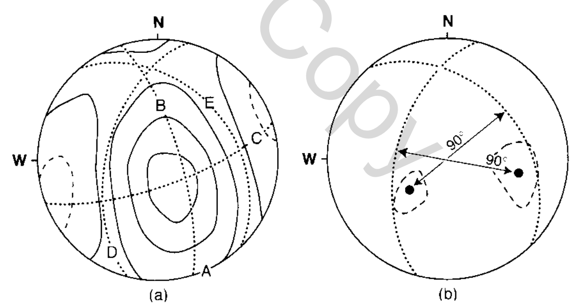

Fig. 5. Lower hemisphere projections showing V_p anisotropy in a horizontal plane (A), in the average foliation (B), the plane of maximum anisotropy (C), planes of minimum anisotropy (D and E) and the orientations of V_s singularities relative to the planes of minimum V_p anisotropy.

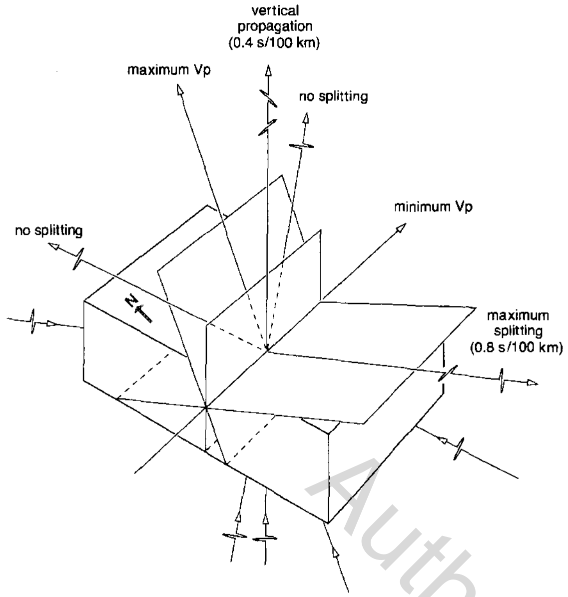

Fig. 6. Schematic diagram of the Twin Sisters massif illustrating propagation directions for maximum and minimum V_p, V_s singularities, maximum V_s splitting and V_s splitting for vertical propagation. Average foliation strikes approximately N20°W and dips steeply to the east.

directions through the Twin Sisters massif is shown schematically in Fig. 6. Vertical propagation produces significant splitting with the fast shear wave polarization direction approximately parallel to foliation (Figs. 3 and 6). Maximum splitting occurs for the propagation along a direction dipping steeply to the north and in the foliation. There are two directions with no shear wave splitting, termed points of singularity (e.g., Crampin and Yedlin, 1981). Thus, orientations of the Twin Sisters massif are possible such that no splitting would be observed from SKS observations. Of significance, these directions are approximately perpendicular to the planes which show little or no Pn anisotropy (Fig. 5b) and are bisected by the direction of maximum compressional wave velocity. Thus, it is possible for highly anisotropic upper mantle to show no azimuthal variations in the seismic velocity of the body-wave phase Pn or shear wave splitting for vertically propagating shear waves.

Teleseismic observations (e.g., SKS) showing no shear wave splitting can be interpreted in several ways. First, it is possible that the shear wave generated at the core–mantle boundary travels through the mantle with its vibration direction parallel to one of the two preferred vibration directions of the anisotropic mantle. In this case, a second shear wave will not be generated and the mantle will appear isotropic. This is analogous to a birefringent crystal on a petrographic microscope at extinction. A second possibility is that the shear wave propagating through the mantle travels along a singular direction, such as those found in this study of the Twin Sisters massif. As in the first case, the mantle will be highly anisotropic but appears isotropic. Third, there is an increasing evidence that in tectonic regions which have undergone multiple deformations, the upper mantle is stratified with layers possessing different anisotropies in both magnitude and direction (e.g., Ozalaybey and Savage, 1995; Christensen et al., 2001). It is possible that the retardation of a split shear wave produced by one layer is cancelled by the anisotropy of an overlying layer giving rise to no observed splitting. Finally, the upper mantle may indeed be isotropic.

Acknowledgements

This research was supported by the National Science Foundation Continental Dynamics Program. The assistance of C. Long and D. Hart is greatly appreciated. H. Kern provided a constructive review of the manuscript.

References

Ando, M., Ishikawa, Y., Yamazaki, F., 1983. Shear-wave polarization anisotropy in the upper mantle beneath Honshu, Japan. J. Geophys. Res. 88, 5850–5864.

Ben Ismail, W., Mainprice, D., 1998. An olivine fabric database: an overview of upper mantle fabrics and seismic anisotropy. Tectonophysics 296, 145–157.

Brown, E.H., Blackwell, D.L., Christenson, B.W., Frasse, F.I., Haugerud, R.A., Jones, J.T., Leiggi, P.L., Morrison, M.L., Rady, P.M., Reller, G.J., Sevigny, J.H., Silverburg, D.L., Smith, M.T., Sondergaard, J.N., Zielger, C.B., 1987. Geologic map of the northwest Cascades, Washington. Geological Society of America, Boulder, CO, Map and Chart Series, vol. MC61, pp. 1–10.

Carter, N.L., AvéLallemant, H.G., 1970. High temperature flow of dunite and peridotite. Geol. Soc. Am. Bull. 81, 2181–2202.

Christensen, N.I., 1966. Shear wave velocities in metamorphic rocks at pressures to 10 kilobars. J. Geophys. Res. 71, 3549–3556.

Christensen, N.I., 1971a. Fabric, seismic anisotropy, and tectonic

history of the Twin Sisters Dunite, Washington. Geol. Soc. Am. Bull. 82, 1681–1694.
Christensen, N.I., 1971b. Shear wave propagation in rocks. Nature 229, 549–550.
Christensen, N.I., Medaris Jr., L.G., Wang, H.F., Jelinek, E., 2001. Depth variation of seismic anisotropy and petrology in central European lithosphere: a tectonothermal synthesis from spinel lherzolite. J. Geophys. Res. 106, 645–664.
Crampin, S., Yedlin, M., 1981. Shear wave singularities of wave propagation in anisotropic media. J. Geophys. 49, 43–46.
Crosson, R.S., Lin, J.W., 1971. Voigt and Reuss prediction of anisotropic elasticity of dunite. J. Geophys. Res. 76, 570–578.
Hess, H.H., 1964. Seismic anisotropy of the uppermost mantle under oceans. Nature 203, 629–631.
Ji, S., Zhao, X., Francis, D., 1994. Calibration of shear-wave splitting in the subcontinental upper mantle beneath active orogenic belts using ultramafic xenoliths from the Canadian Cordillera and Alaska. Tectonophysics 254, 1–27.
Kern, H., 1993. P- and S-wave anisotropy and shear-wave splitting at pressure temperature in possible mantle rocks and their relation to the rock fabric. Phys. Earth Planet. Inter. 78, 245–256.
Kern, H., Burlini, L., Ashchepkov, I.V., 1996. Fabric-related seismic anisotropy in upper-mantle xenoliths: evidence from measurements and calculations. Phys. Earth Planet. Inter. 95, 195–209.
Kumazawa, M., Anderson, O.L., 1971. Elastic moduli, pressure derivatives and temperature derivatives of single crystal olivine and forsterite. J. Geophys. Res. 74, 5961–5972.
Long, C., Christensen, N.I., 2000. Seismic anisotropy of South African upper mantle xenoliths. Earth Planet. Sci. Lett. 179, 551–565.
Mainprice, D., Silver, P.G., 1993. Interpretation of SKS-waves using samples from the subcontinental lithosphere. Phys. Earth Planet. Inter. 79, 257–280.
Misch, P., 1966. Tectonic evolution of the northern Cascades of Washington State. In: Tectonic History and Mineral Deposits of the Western Cordillera. Symposium Canadian Institute of Mining and Metallurgy, Montreal, pp. 101–148.
Morris, G.B., Raitt, R.W., Shor, G.G., 1969. Velocity anisotropy and delay-time maps of the mantle near Hawaii. J. Geophys. Res. 74, 4300–4316.
Nicolas, A., Boudier, F., Boullier, A.M., 1973. Mechanisms of flow in naturally and experimentally deformed peridotites. Am. J. Sci. 273, 853–876.
Ozalaybey, S., Savage, M.K., 1995. Shear-wave splitting beneath the western United States in relation to plate tectonics. J. Geophys. Res. 100, 18135–18149.
Ragan, D.M., 1963. Emplacement of the Twin Sisters Dunite, Washington. Am. J. Sci. 261, 549–562.
Savage, M.K., 1999. Seismic anisotropy and mantle deformation: what have we learned from shear wave splitting? Rev. Geophys. 37, 65–106.
Silver, P.G., Chan, W.W., 1988. Implications for continental structure and evolution from seismic anisotropy. Nature 335, 34–39.
Smith, G.P., Ekstrom, G., 1999. A global study of Pn anisotropy beneath continents. J. Geophys. Res. 104, 963–980.
Soedjatmiko, B., Christensen, N.I., 2000. Seismic anisotropy under extended crust: evidence from upper mantle xenoliths, Cima volcanic field, California. Tectonophysics 321, 279–296.
Vinnik, L.P., Kosarev, G.L., Makeyeva, L.I., 1984. Anisotropy in the lithosphere from the observations of SKS and SKKS. Proc. Acad. Sci. USSR 78, 1335–1339.