Laboratory determination of velocity anisotropy

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Summary

Over the past decade technological advances have brought us the capacity to acquire and process high-resolution seismic data in seismic exploration. The physical properties of crust rocks are anisotropic to some extent as demonstrated by data from seismic studies, borehole logs and laboratory. In fact, anisotropy is a fundamental property of rocks. But, our understanding of the anisotropic properties of many rocks is still limited. Consideration of anisotropy in seismic analysis and processing will improve their resolution. So, it is important to understand the intrinsic properties of the rocks through which the seismic waves pass.

This study describes a set of ultrasonic laboratory techniques to measure and calculate the P and S wave velocity and anisotropy. The relationship between wave velocities and anisotropy and their directional dependence at pressure are displayed. In the particular material studies, the P and S wave velocities exhibit a weak anisotropy causing by marked micro-crack network and the lattice preferred orientation (LPO) of the minerals in the sample. Optical microscopy study shows a micro-cracks network was created and guided in the petrogenetic and metamorphic processes.

Experiment and Measurement

In a rock core with axially aligned cracks or other intrinsic anisotropy, the compressional waves travel fastest parallel to the dominant crack plane and slowest perpendicular to this orientation. Also, the shear wave velocities will vary with azimuth, because polarized shear waves will encounter the crack array in all orientations. The Rock Physics Laboratory has developed a Velocity Anisotropy Measurement System that can make high-resolution measurements of many velocity components over the complete volume of rock cores. There are a number of high speed digital oscilloscopes that are used primarily in ultrasonic measurements of P-wave and S-wave speeds through materials under pressures as great as 300 MPa and at different temperatures. As well, ultrasonic transducers were developed for use in detailed elastic wave anisotropy studies to more fundamental porous media measurements.
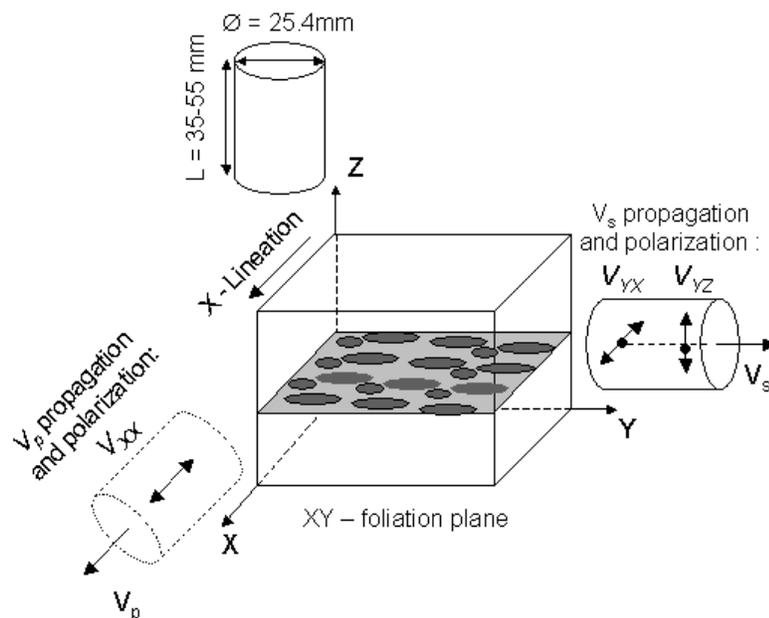
Figure 1. The method of mutually orthogonal plugs for measuring velocity and anisotropy (After Cholach and Schmitt, 2004)

In this example study, P- wave and S- wave measurements were made on cylindrical cores (2.54 cm diameter × 3.5 to 5.5 cm length). The sample plugs were drilled at the mutually orthogonal directions as illustrated in Figure 1, along one of the three axes of symmetry. The cores were drilled from the rock specimen in directions with respect to visible textural feature. Each specimen has one cut perpendicular to foliation plane and at least one core parallel to the foliation plane. In the case of visible lineation direction two cores were cut within the foliation plane, parallel and perpendicular to the lineation direction. If possible, additional cores were cut in the same direction to investigate the heterogeneity within a given specimen. The ends of these cores were flattened parallel using a surface grinder. After cutting and flattening, the cores were dried in the vacuum oven for over 6 hours at a temperature 80^0C. Mass densities were obtained by the Archimedean displacement method to an uncertainty of better than ± 0.5 %. The variations in density between cores obtained from the same specimen are generally less than 1%, indicating a consistency of the mineral composition within a given sample. The porosities of the samples were not determined but typically less than 1 % at room temperature and pressure. The fact that the submerged masses of these samples did not appreciably change during the density measurement is indicative of low permeability and porosity. The macrostructure and composition of samples were identified by thin sections. Further, SEM photos and X- ray diffraction were used to investigate the microstructure and composition of the rock and minerals. Photomicrography from the thin sections perpendicular and parallel to the foliation illustrating the microstructure are shown in Figure 2.
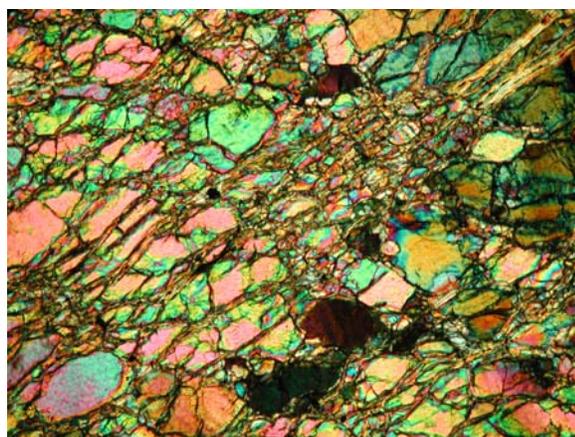
| Normal to the foliation plane | Parallel to the foliation plane |
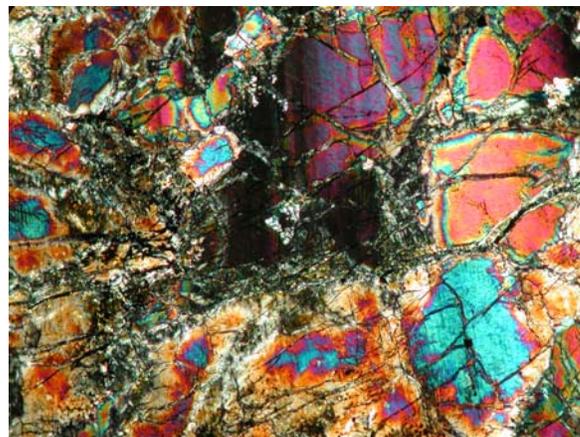
Figure 2. Photomicrographs from the different directions illustrate the various rock fabrics.

The laboratory velocity measurements were carried out using a pulse transmission technique (e.g., Kern, 1982). Transmitting and receiving transducers were mounted at the opposing ends of the cylindrical samples. P- wave and two S-wave measurements were made on all the cores in longitudinal mode. The piezoelectric ceramics (2.54 cm diameter, 1-MHz frequency, P- wave transducers or 18 × 18 mm size, 1-MHz frequency, S- wave transducers) were placed at both ends of the cores for the P- and S- wave measurements, respectively. The S- wave ceramics provide a mechanical pulse polarized parallel to the ends of the samples and care need to be taken to ensure that the polarization directions of both transverse mode ceramics were properly aligned to each other and appropriately oriented with respect to the rock's principal textural X, Y, Z axes. One or two sets of sample could be used for each run. Each sample requires 1 P- wave and at least two orthogonally oriented S- wave runs. The piezoelectric ceramics were mechanically damped in order to broaden the overall transducer bandwidth. The attached ceramic transducer and rock sample were then hermetically sealed to exclude the pressure vessel fluid from the rock and this assemblage placed in the pressure vessel. A state of near-hydrostatic stress is achieved by increasing confining pressure at room temperature.

A conventional pulse transmission technique (Molyneux and Schmitt 1999, 2000) was used to obtain P and S wave velocities using longitudinally and transversely polarized piezoelectric ceramics, respectively. The transmitting ceramic was activated by the fast rise-time, and generated the appropriate mechanical wave. The response of the receiving ceramic was recorded at rates from 4 ns per sample to 10 ns per sample depending on the digital oscilloscope used. A typical final waveform trace was constructed from 100 – 500 progressively stacked records to reduce random noise. The waveform was transferred to a computer to be stored for later transit time determination. In each run, waveforms were acquired over the range of confining pressure from 0 ~ 300 MPa with an interval of 5 MPa and back. Pressure is applied not so much to mimic *in situ* conditions but to close as much of the micro-crack porosity in the rocks as possible in order that the velocities are representative of the intrinsic mineralogical texture of the sample. The results from one S- wave run consisting 79 traces highlights the well-know decrease in pulse transit times and

increment in amplitude with increasing confining pressure in Figure 3. Figure 4 is a S- wave pulse train taken from one of the waveforms in Figure 3. The pulse first extremum was used to determine the transit time. In Figure 4 this is the first trough.
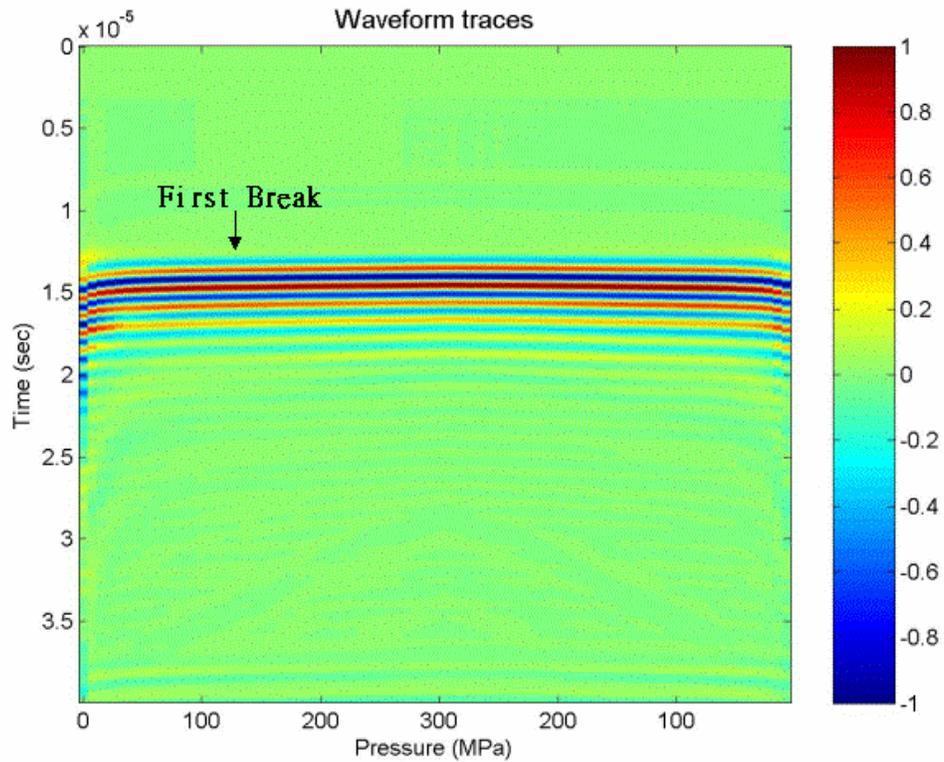
Figure 3. Waveform traces during one pressure cycle.
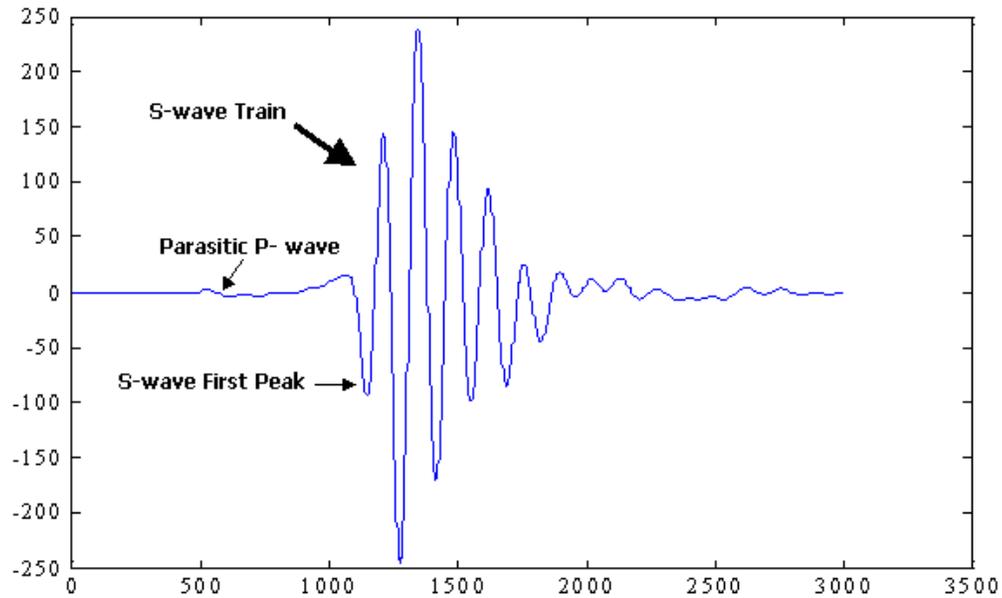
Figure 4. An example of a typical shear wave trace from Figure 3.

Results

Studies on the relationship between velocity anisotropy and confining pressure are an important component of rock physics studies, particularly these rock types play an important role in the lithology of the upper lithosphere. The anisotropy of P and S wave velocity is an important characteristic of crust and mantle rocks. Determination of lithological and physical properties of these rocks is essential for proper interpretation of the nature of observed seismic reflectors. In the past, much laboratory (e.g., Christensen, 1966; Barruol and kern, 1996) and theoretical work (e.g., Baker and Carter, 1972; Siegesmund et al., 1989; Mainprice and Silver, 1993; Ji et al., 1994) has been devoted to the nature of P and S wave anisotropy in the Earth's crust and upper mantle. Christensen (1966) has correlated the volume of serpentinization with the decrease of P-wave velocity. Horen et al. (1996) have explored the relationships between degree of serpentinization and P- and S-wave velocities anisotropies. Nur (1971) discussed the effects of oriented micro-cracks on elastic wave propagation. The lattice-preferred orientation (LPO) has been taken into account in previous theoretical calculations of P- and S-waves velocities and seismic anisotropy of mantle rocks.

In this study, the seismic properties and their directional dependence have been measured in eleven serpertinized dunite samples from Vourinos Ophiolite (France). The compressional velocities were measured to confining pressures of 300 MPa in mutually orthogonal directions to investigate anisotropic properties with respect to the visible textural properties of rocks. The shear-wave velocities were measured at two orthogonal polarizations for each direction to determine shear-wave splitting and correlate it with P-wave anisotropy. Once the material is anisotropic there will generally be compressional waves propagating with different velocities in the different directions, and the polarizations of two distinct shear waves propagating will lead to the shear wave splitting in the orthogonal direction. In the case of waves propagating along the lineation Y, the three elastic waves P- wave [yy], S-wave [yz], and S- wave [yx] will exist in such a situation. The P- wave propagating along the Y-axes is designated by P [yy], and two shear waves propagating in the Y direction polarized in the yz and yx plane are designed S [yz], and S [yx]. Measurements of velocities and anisotropy with different pressures are shown in Figure 5.
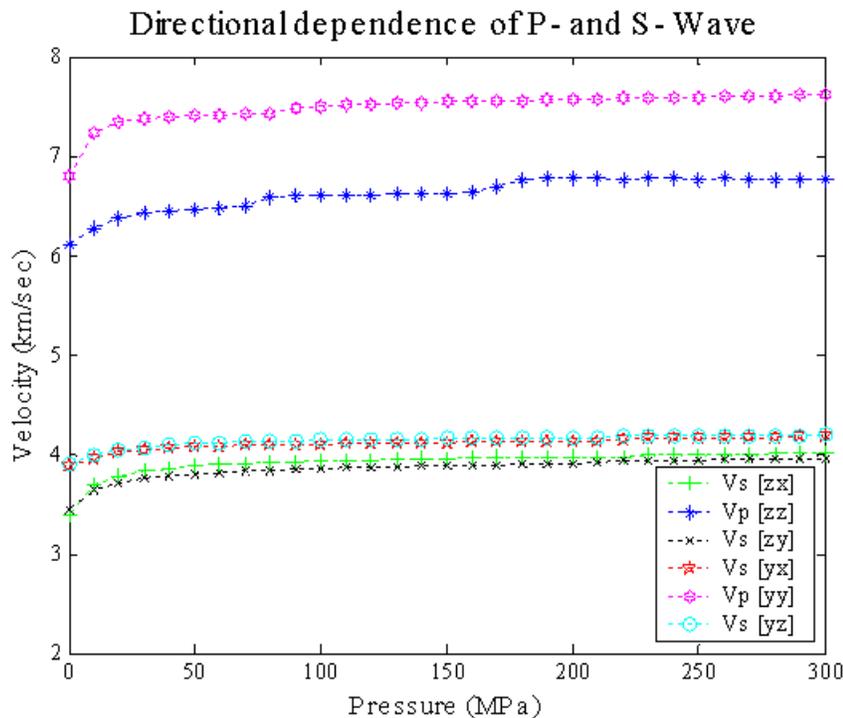
Figure 5. Measurements of Velocities and Anisotropy

The P and S wave velocity and anisotropy data measured at ultrasonic laboratory measurement on eleven samples of dunite exhibit a marked lattice preferred orientation (LPO) of olivine and the serpentine lattice. Optical microscopy study shows micro-cracks guided by the serpentine (lizardite) penetrative network. Observed Vp anisotropy varied from quasi-isotropic to the weak

anisotropic (A_p=11%). Pressure invariance of observed P-wave anisotropy and shear-wave splitting indicates that the micro-cracks play an important role at pressures less than 100MPa, and that the lattice preferred orientation (LPO) is mainly responsible for the measured seismic anisotropy in these rocks.

Acknowledgements

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