Laboratory comparison between seismic and magnetic anisotropy

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2005 CSEG National Convention

Summary

Rock fabrics deduced from either the anisotropy of magnetic susceptibility or of seismic anisotropy have been widely discussed; on this basis one might expect there to be some correlation between their characteristics. However, whether a general relationship exists between magnetic susceptibility and seismic anisotropy and what its significance might be remains unknown and there remains room for future studies. Pindos and Vourinos ophiolite with its high magnetic susceptibility is a good candidate for comparison between the anisotropy of magnetic susceptibility (AMS) studies and seismic anisotropy; the study of shales will follow. Comparing the AMS and seismic anisotropy indicates that generally both directions and intensities of the magnetic susceptibility anisotropy and the seismic anisotropy coincide. These results motivate the development of additional method to use the fabric, as deduced from simple and fast AMS measurements, as a proxy for finding the directions of elastic anisotropy in traditional ultrasonic laboratory methods.

Laboratory determination of seismic anisotropy

The laboratory velocity measurements were carried out using the ultrasonic pulse transmission technique (Birch1961, Kern1982). A conventional pulse transmission technique (Molyneux1999, Molyneux2000) was used to obtain P- and S-wave velocities using longitudinally and transversely polarized piezoelectric ceramics, respectively. In our implementation a high voltage (200V) rapid rise-time (~8 ns) step-pulse from a generator (model 5800, PANAMETRICS™) activates the mechanical vibrations in the source piezoelectric transducer. These mechanical vibrations travel through the rock sample and are received at the end by the receiver piezoelectric transducer that transforms the mechanical vibrations back into electrical signals (instrument setup shown in Figure 1).

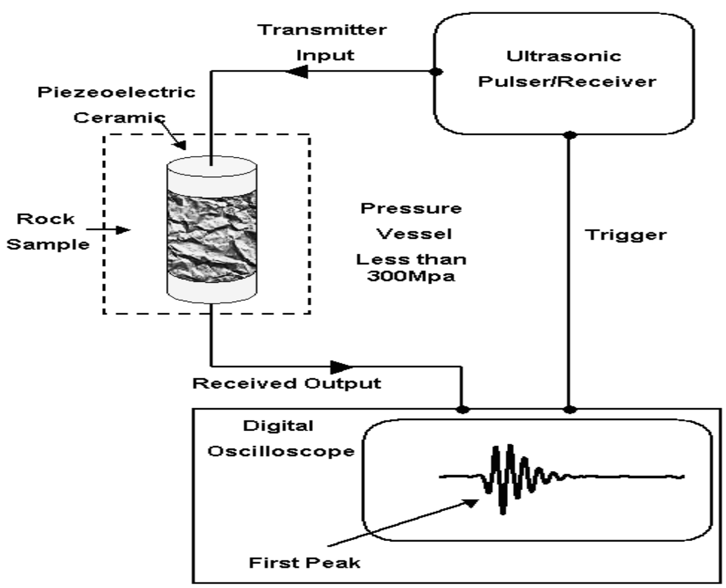

Figure 1. Schematic showing acoustic experiment setup

There are a number of high-speed digital oscilloscopes (GaGe™, Model No. 400-586-203) 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. The digital oscilloscope used in the experiment receives two signals: the trigger signal from the pulse generator to synchronize the oscilloscope with the initiation of the pulse, and a delayed signal that has traveled through the rock sample to the receiving transducer. The signals received by the oscilloscope are recorded in the computer. Then, the Matlab programs are developed to pick the travel time. In practice, we choose the first peak or trough to pick the first arrival. This provides a good estimation of the travel time. P-wave and two S-wave measurements were made on all the cores in longitudinal mode. Each sample requires 1 P-wave and at least two orthogonally oriented S-wave runs. In each run, waveforms were acquired over the range of confining pressure from 0 to 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.

Magnetic susceptibility and AMS

The anisotropy of low-field magnetic susceptibility (AMS) is usually determined after measuring the susceptibility of a rock specimen along different directions. This enables one to calculate the AMS tensor, which can be represented by an ellipsoid with minimum (K_3), intermediate (K_2) and maximum (K_1) susceptibility axes. The ratios of the pairs of the principal susceptibilities are commonly used to characterize the magnetic fabric. There are different methods that can to be used measure magnetic anisotropy. Each method provides information that enable the anisotropy of magnetic susceptibility to be described in terms of a triaxial ellipsoid. Jelinek (1977) used the 15-position scheme. Borradaile (1995) generally summarized and reviewed measurement schemes. In this study, the AMS was measured on a Bartington MS2B Sensor in conjunction with the AMSWIN-BAR software, operating at a fixed frequency of 0.465 kHz (LF), with an applied field of 250 μT. The three principal axes defining the AMS ellipsoid are determined from the 18-position orientation scheme.

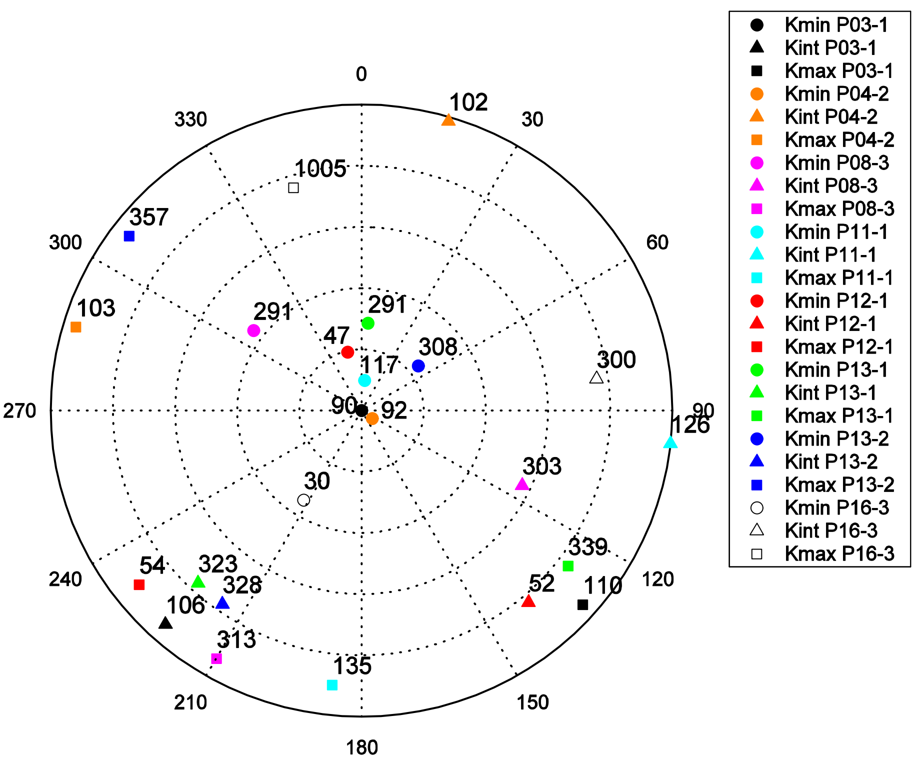

Figure 2. The magnitude and direction of all samples' AMS principal axes

The magnitude and direction of all the samples' principal axes are shown in Figure 2. The minimum K axis shows the non-random distribution with its direction clustering in the direction perpendicular to textural planes (this is, the direction of Z-axis in seismic anisotropy, which is perpendicular to the cutting plane with 90 degree inclination in Figure 2). The samples P 08-3 and P16-3 deviate from this trend, due to the fact that the textures were not easily discernable in these two rocks. Their sampling orientation was neither parallel nor perpendicular to the foliation. The maximum and intermediate axes have no special declination trend, as there is no orientation with their original geographic position. Their inclination, however, is mostly near the edge of the polar plot. This further suggests that the orientation of the sampling was closely perpendicular to foliation.

According to the mean susceptibility range of samples (99 ~444.8 $\times 10^{-5}$ SI unit), the bulk AMS is due to the combination of the preferred crystallographic orientations of the paramagnetic matrix minerals in major phase of the rock, and the anisotropy of magnetite grain in accessory phase (Tarling and Hrouda, 1993). The Curie temperature (578 °C) proves the presence of pure magnetite in the thermomagnetic analysis.

Result and discussion

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 3.

Laboratory measurements on these materials include compressional and shear-wave velocities at confining pressures to 300 MPa, density, velocity anisotropy, and shear-wave splitting. The experimental seismic velocities offer the average calculations of anisotropies, elasticity, and symmetries for the whole mineral assembly of rocks. Magnetic fabrics, sensitive indicators of low-intensity strain, were further obtained from AMS measurements on the same samples. The directions of acoustic and magnetic anisotropy compare favorably. A possible reason for this correlation is that the magnetic fabrics are thought to be representative of the secondary magnetite produced during serpentinization, and also from the primary paramagnetic minerals assemblage that causes the velocity anisotropy. The magnetic fabric of a few secondary magnetite originated from serpentinization along fractures that crosscut olivine grains might mimic the principal rock texture to some extent.

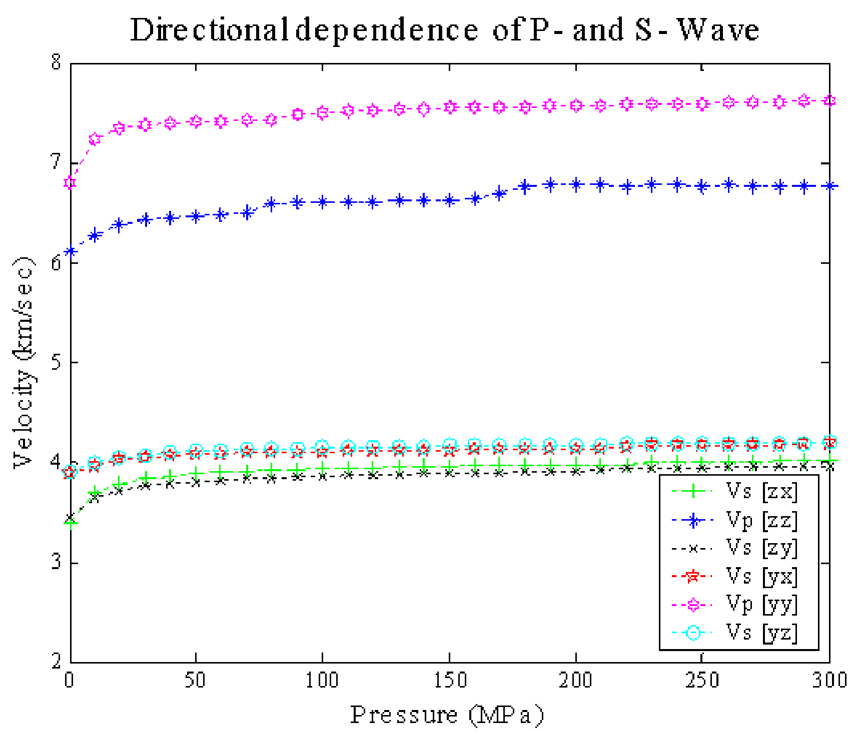

Figure 3. Measurements of Velocities and Anisotropy

A comparison of the orientations and the intensities was carried out to look for a correlation between magnetic fabrics and seismic anisotropy. The laboratory velocity investigation shows that the slow Vp direction usually along the Z-axis direction. The AMS fabric orientation is displayed for each sample in Figure 2, which suggests that the Kmin axes of most samples cluster at a direction roughly perpendicular to the rock's principal texture foliation, this latter having been selected only on the basis of visual examination of the samples. Based on AMS and seismic anisotropy experiments, the rock textures deduced from magnetic fabric and the seismic anisotropy generally compare favorably in the laboratory measurements. That is, if the preferred orientation of the AMS carrier minerals consists of original paramagnetic minerals or if the secondary magnetic minerals mimic the orientation of the main phases, the AMS and seismic anisotropy are well correlated. Thus, the AMS may offer useful preliminary information with regard to the foliation and the mineral fabric for the whole rocks, regardless of whether it is caused by crystalline or shape anisotropy. This may greatly aid laboratory work because even if we know the crystal anisotropy of olivine and other minerals, it remains difficult to properly select the anisotropic direction of rocks for measurements. As a result, it maybe useful to carry out AMS prior to machining of samples for elastic anisotropic measurements in order to guide the sample preparation.

Even though the serpentine group minerals have a complex composition, we still hope to try some quantitative comparison between the intensities and directional dependence between AMS and the seismic anisotropy. The results show that there is not only a coincidence in the direction, but also possible in the intensities between AMS and seismic anisotropy. The AMS are more sensitive to the composition of samples. P-wave velocities (200 MPa) ratio Vpzz / Vp yy and magnetic susceptibility ratio Kzz / Kxy in Z-axis and along X and Y plane are listed in table 1. The ratios show that both magnetic susceptibility and velocity have the smaller value along the Z-axis than along XY plane. Kzz is the average magnetic susceptibility along the Z-axis, and Kxy is the average magnetic susceptibility along the X and Y-axis. Kzz / Kxy display a directional dependence in the magnetic susceptibility similar to that for the measurement of velocity anisotropy, but the relative difference of velocities are much smaller than the magnetic susceptibility.

	P13-2	P13-1	P11-1	P08-3	P04-2	P03-1	P12-1	P16-3
Kzz mean	264.8	246.2	97.6	243	79.2	79.2	39.9	439.2
Kxy mean	329.5	314.3	125.4	292.5	105.1	105.1	50.9	627.3
Kzz/Kxy	0.8	0.78	0.78	0.83	0.75	0.75	0.78	0.7
Vp zz(m/s, 200MPa)	5632	5270	7454	6234	6428	6428	6777	6035
Vp yy(m/s, 200MPa)	5672	5359	7566	6546	6974	6974	7568	6174
Vp zz/Vp yy	0.99	0.98	0.99	0.95	0.92	0.92	0.9	0.98

Table 1. P-wave velocities and magnetic susceptibilities along Z-axis and within XY plane

Conclusions

Determining rock fabric from the magnetic fabrics could be a useful proxy for petrofabric measurement. We should obtain more useful information quantitatively concerning the factors to influence the relationship between the intensity of magnetic susceptibility and the rock magnetic fabric for more pure minerals and typical rocks. These may further allow us to compare rock fabrics with the magnetic fabrics.

Acknowledgements

- Technical assistance by L. Tober, Dr. C.D. Rokosh, D. Collis, R. Hansen, T. He, and A. Berthelot.
- Funding by the Canada Research Chair Program and NSERC.
- Techniques are being developed with the support of Course funding provided by AERI.

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