Seismic anisotropy in cracked crystalline rock from Outokumpu, Finland

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SUMMARY

Lattice and shape preferred orientation of minerals, along with aligned fractures and microcracks, is expected to cause significant seismic velocity anisotropy in crystalline rocks. As seismic surveys in hard rock environments become more common, quantifying and accounting for this anisotropy in seismic processing becomes increasingly important.

Outokumpu, Finland is the site of a historic base metal mine and is a classical ore province known for its Cu-Co-Zn sulphide deposits. The 2.5 km deep ICDP borehole shows the lithology in the area of the Outokumpu 2006 2D seismic survey to be primarily composed of a biotite-rich schist. Three walk-away VSP profiles were used to quantify the tilted orthorhombic in-situ anisotropy. Laboratory measurements of the qS1, qS2 and qP waves along the axial directions and in select off-axis directions at confining pressures from 10-200 MPa, and effective medium modelling were used to further inform the seismic anisotropy of the schist. Strong anisotropy is observed both in-situ and in the laboratory measurements. A 3D velocity distribution is calculated from modelling of these results.

Key words: vertical seismic profile (VSP), crystalline rock, anisotropy, cracks, effective medium theory.

INTRODUCTION

Outokumpu, Finland is the site of a historic base metal mine and is a classical ore province known for its Cu-Co-Zn sulphide deposits. In the past several years, large crustal scale seismic reflection profiles collected by the Geological Survey of Finland, University of Oulu and University of Helsinki as part of the Finnish Reflection Experiment (FIRE) project identified a strong reflector in the Outokumpu area which had a high probability of being associated with an ore body. This sparked renewed interest in exploration and helped motivate the drilling of a 2.5 km deep fully cored borehole in Outokumpu. The borehole was fully logged, including borehole televiewer (BHTV). In May 2006, a high resolution seismic survey was conducted using the borehole to further refine the geological model of the area. The survey included a zero offset VSP, a far offset VSP, a multi-azimuth multi-depth walk-away VSP and a reflection/refraction profile.

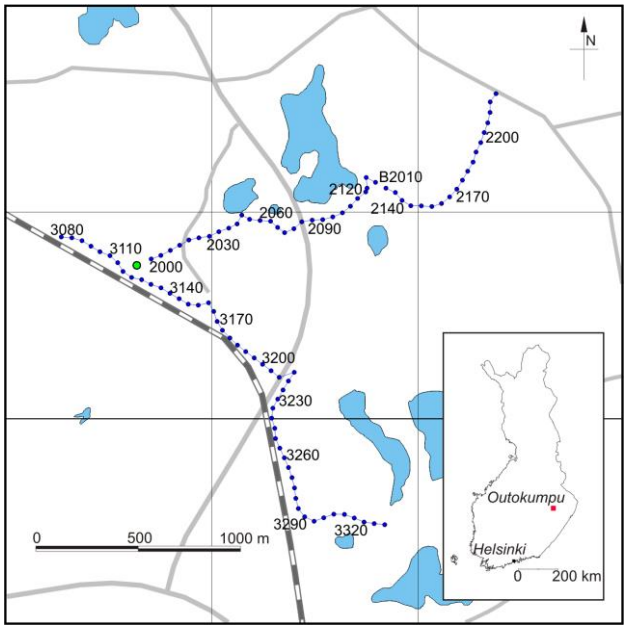

Figure 1: Map showing the location of 2.5 km deep Outokumpu borehole in green, along with the two seismic lines in blue. A map of Finland showing the location of Outokumpu is included as an inset.

The geology of the subsurface shows that it is relatively simple. The borehole cut mica-rich schist to a depth of 1.3 km, where it is intercepted by a 200 m thick section of Outokumpu-assemblage rock (mainly serpentinite and diopside-tremolite skarn). Below this, the lithology returns to being dominated by mica-rich schist, but with increasingly thick intersections of pegmatitic granite (Figure 2). Anisotropy in the area is expected to be caused by lattice-preferred orientation of the biotite in the schist, and aligned microcracks or fractures. This abstract examines anisotropy in a fractured crystalline terrane, and allows a comparison between experimental and theoretical anisotropy measurements.

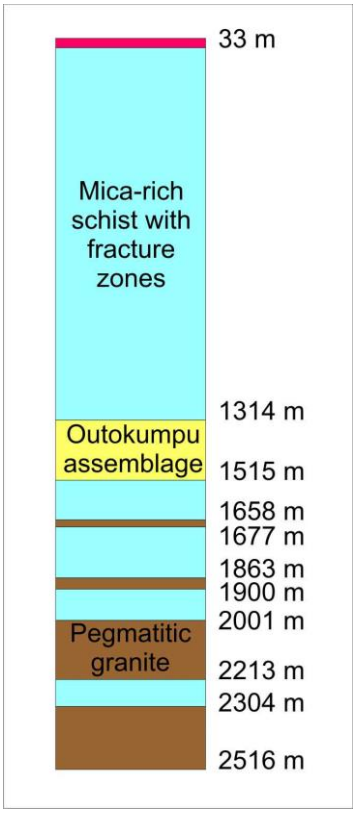

Figure 2: Borehole geology showing the strongly schist dominated lithology of the core, particular above 1300 m depth.

METHOD

The walk-away VSP survey was conducted using a vertical seismic vibrator source employing linear 8 s sweeps with frequencies 15-250 Hz. A three component downhole receiver was used, and was positioned at depths of 1000, 1750 and 2500 m in the borehole. All data was recorded using a 1 ms sampling rate.

The shot points of the seismic lines (Figure 1) were typically 20 m apart. The lines were each approximately 2 km long, and lay along a northeast and principally southeast azimuth from the borehole (hereafter referred to as the NE and SE lines). Seismic reflection and refraction profiles were acquired simultaneously with the walk-away VSP data The seismic refraction data was integral to the processing using 14 Hz single component surface geophones placed at 4 m intervals, and were integral to the processing of the walk-away VSP results as the data required significant static corrections (Figure 3).

Static corrections for the walk-away VSP were calculated from a near surface model created using traveltime inversion of the seismic refraction measurements. The walk-away VSP was further processed through the removal of strong harmonics within the data using a block subtraction technique, the application of a recti-linearity filter to isolate body waves and the application of a polarization filter to separate qP-, qS1-, and qS2-waves.

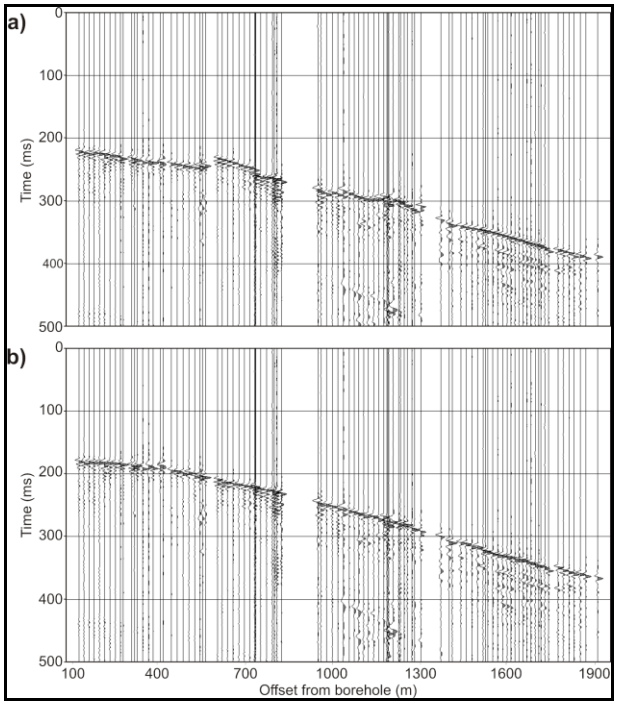

Figure 3: Seismic traces from the NE walk-away VSP data set, with receiver at a depth of 1000 m, rotated and filtered using a harmonic and polarization filter. a) Showing the P-wave arrival before and b) after P-wave static corrections.

A τ-p transform was applied to the walk-away VSP data, to allow the measurement of the phase velocity of the seismic signal as a function of phase angle of propagation. The transform allows the calculation of interval velocities, resulting in the ability to measure velocities between 1000-1750 m and 1750-2500 m depth in addition to the velocities measured from the surface to the receiver depth. Experimental qP-wave velocities were recovered for all depths and azimuths (Figure. 4), while qS-wave velocities were recoverable only when the receiver was 1000 m downhole due to the comparatively lower signal to noise ratio and frequencies of the qS-waves.

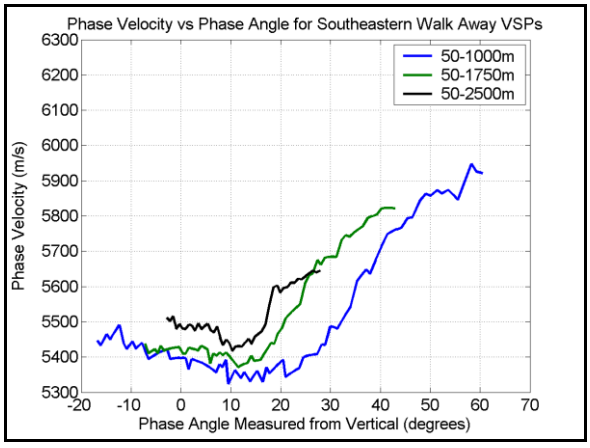

Figure 4: Phase angle vs. phase velocity measured by τ-p transform of the 1000, 1750 and 2500 m walk-away VSPs along the SE seismic line showing significant anisotropy over the measured angles.

Theoretical phase velocities can be calculated directly from the elastic tensor of a material if it is known. In order to expand the walk-away VSP measurements measured along only two azimuths and with a limited range of angles into a full three dimensional velocity model, a theoretical model was fit to the experimental qP-wave velocity measurements. The 1000 m walk-away VSP measurements were chosen for modeling purposes as the seismic waves propagate through uniform schist to this depth. This allowed the development of a simpler model since the characterization of only a single rock type is required. In addition, the 1000 m walk-away provided the sole measurement of qS-waves for comparison with a model. In order to represent the fractured schist of this region, Schoenberg's (1980) formulation was used to forward model the elastic tensor of an orthorhombic medium with aligned cracks. The model required an initial elastic compliance tensor representing the unfractured schist, S_b, to be added to the compliance tensor of the fractures, S_f. The resulting tensor was inverted to yield the elastic stiffness tensor, C, of the fractured schist:

$$C_{ijkl} = [S_{ijkl_b} + S_{ijkl_f}]^{-1}$$

The stiffness tensor was then used in conjunction with the Christoffel equations to find theoretical phase velocities. These theoretical velocities were compared to the walk-away VSP measurements using a least-squares fit to find the best representation of the fractured schist.

The initial elastic tensor representing the unfractured schist was estimated from velocity measurements made on core samples from the borehole by Kern *et al.*(2008) at a pressure of 200 MPa. Kern *et al*. measured P-wave velocities in all directions on a spherical sample, and measured S-wave velocities along the axial directions. A theoretical elastic tensor for the unfractured schist was estimated by fitting these velocities. The elastic tensor representing the aligned fractures, based on Schoenberg's (1980) model, was varied through a range of possible values. Both tensors were rotated through a full complement of angles before being added together to allow for any possible orientation of the schist and fractures. The resulting best fit (Figure 5) yields information on the orientation of the foliation plane of the schist, the lineation of the schist, and the orientation of fractures within the schist. These theoretical orientations were compared to other measurements in order to assess the quality of the theoretical result.

Analysis of BHTV data was completed to determine the orientation of any aligned fractures within the borehole for comparison with theoretical model results. Ultrasonic measurements of core samples from borehole depths of approximately 800, 1100, 1200 and 1300 m were also undertaken to determine the off-axis velocities of the S-waves for comparison with the velocities estimated for the theoretical elastic tensor of the unfractured schist (Figure 6). Small piezoelectric P- and S-wave transducers were glued directly on each of the four sides of the cylindrical core sample and on the top and bottom of the sample, allowing measurements in all axial directions and at angles of 30º and 45º from vertical.

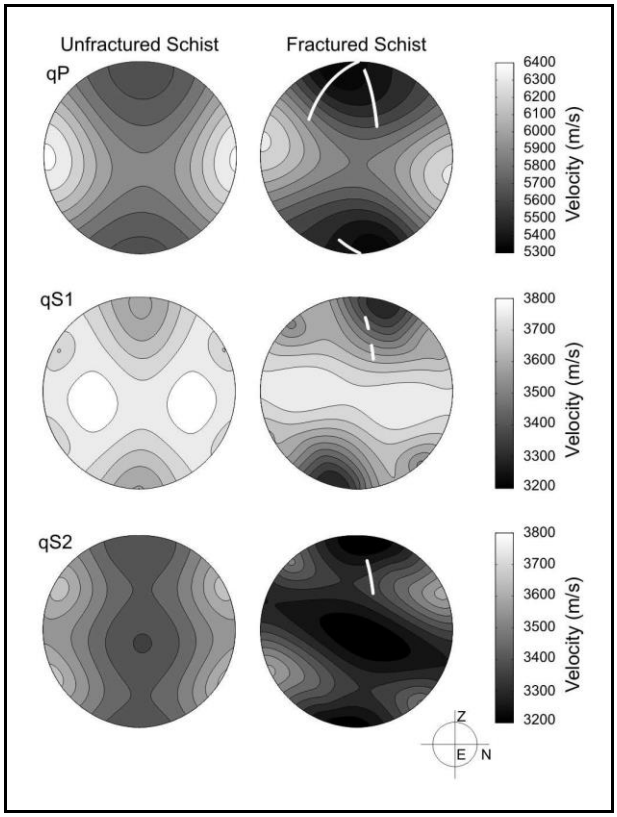

Figure 5: Equal area projections of the theoretical phase velocities of the unfractured (left column) and fractured (right column) schist, showing the increase in qP- and qS-wave anisotropy caused by the addition of a fracture set. White lines on the fractured schist denote where the walk-away VSP data lie on the projection. qP-wave velocities are contoured every 100 m/s and qS-waves every 50 m/s. The axes correspond to east, north and vertical in a right handed coordinate system.

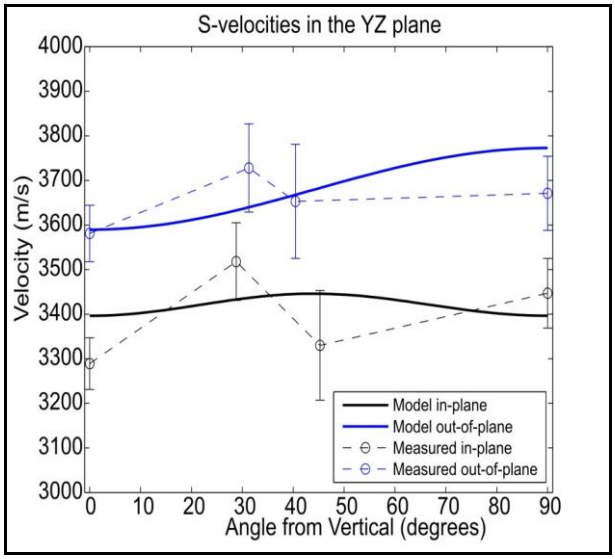

Figure 6: qS1- and qS2-wave velocities measured in the plane perpendicular to foliation and lineation of the schist on a core sample from 1100 m depth in the borehole show good agreement with the theoretical model which was fit to the in-situ walk-away VSP measurements.

CONCLUSIONS

Strong anisotropic is observed in the 1000 m walk-away VSP, particularly in the southeastern direction. Less anisotropy is observed to the northeast, likely as a result of the orientation of the orthorhombically symmetric anisotropic velocity distribution of the schist.

Good agreement is reached between the theoretical model and the experimental results for the qP-wave velocities, allowing velocity predictions for additional angles and azimuths that were not measured by the walk-away VSPs. The theoretical model predicts the foliation plane of the schist to be nearly horizontal, which correlates with the known geology of the area. The qS-wave walk-away VSP measured velocities correlate well with the model results, however, some offset is observed. Comparison of the theoretical qS-wave velocities to laboratory measured velocity anisotropy yields a good fit for some, but not all, measurements. Additionally, the BHTV data does not agree well with the theoretical alignment of fractures. The model will be refined further by integrating the off-axis qS-wave velocities measured in the laboratory into the estimate of the elastic tensor of the uncracked schist. This will allow more conclusive interpretation of the causes, magnitude and orientation of anisotropy in the area, and may allow a measure of the applicability of Schoenberg's (1980) model to prediction of anisotropy in crystalline terrane.

The measurement of seismic velocity anisotropy in the Outokumpu area is an important component of any further seismic studies in the area, and the development of a three dimensional anisotropy model removes any limitations on the orientation or layout of future seismic surveys. The substantial anisotropy observed in Outokumpu and other hard rock environments must be accounted for as the incorporation of anisotropic velocity information significantly improves the ability to correctly locate subsurface features. As the mineral exploration industry increases their use of seismic exploration, these measurements and the techniques developed will be of significant importance in the processing and interpretation of seismic data.

ACKNOWLEDGEMENTS

Field work was made possible by a grant from the International Continental Scientific Drilling Program and by the NSERC Discovery grant of DRS. Field acquisition of this data was greatly assisted by M. Welz, L. Tober, D. Meillieux and E. Bianco from the University of Alberta; S. Heinonen, M. Malm and J. Keskinen from the University of Helsinki, personnel from the Geological Survey of Finland and the GFZ-Potsdam wireline crew.

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