Anisotropic Velocity Model of a Fractured Formation using a High Resolution VSP Survey and Forward Modeling

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Summary

In May 2006 the University of Alberta, in conjunction with the University of Helsinki and the Geological Survey of Finland, conducted a high resolution seismic survey using the 2.5 km deep ICDP (International Continental Scientific Drilling Program) borehole in Outokumpu, Finland. This abstract describes the processing techniques used to determine experimental anisotropic velocities from the seismic survey data as well as the forward modeling used to expand the experimental measurements into a three dimensional velocity model.

Introduction

Several large crustal scale seismic reflection profiles were conducted over the past several years by the Geological Survey of Finland and the Institute of Seismology at the University of Helsinki. A strong reflector, with a high probability of being associated with an ore body, was discovered in the section of the profile that passed through the town of Outokumpu, the site of a decommissioned base metal mine. This discovery motivated further research in the geology of the area. A 2.5 km deep, fully cored, borehole was drilled, and remains open for scientific use. In May 2006 a high resolution seismic survey was conducted using the borehole to study the anisotropy in the area. The geology of the subsurface shows it is composed of crystalline-type rocks, and principally of a mica-rich schist. The anisotropy in the area is expected to be caused by the lattice-preferred orientation of biotite in the schist as well as by aligned fractures present in the subsurface.

Method

The May 2006 survey consisted of a zero offset VSP (vertical seismic profile) with 2 m depth increments, a far offset VSP with 25 m depth increments, a reflection/refraction survey in two azimuthal directions (to the Northeast and Southeast), with the seismic lines intersecting at the borehole, and a set of walk-away VSPs along the two azimuths, with the receiver located at depths of 1000, 1750 and 2500 m. The University of Alberta IVI minivib™ was used as a source, with linear taper 8 s sweeps from 15-250 Hz. Additionally, the Geode acquisition system, the GFZ-Potsdam logging truck and a downhole 3-component geophone package were used in data acquisition.

The walk-away VSP data sets required static corrections due to topographical changes and a heterogeneous near surface. A tomography model of the near surface (fig. 1) was created using travel-time inversion of the refraction data, allowing the walk-away data to be corrected to a datum elevation. Further processing included the removal of 50 Hz harmonic noise, the application of a recti-linear polarization filter in order to increase the signal to noise ratio of the P- and S-waves, and a directional filter to isolate each wave within the data (fig. 2).

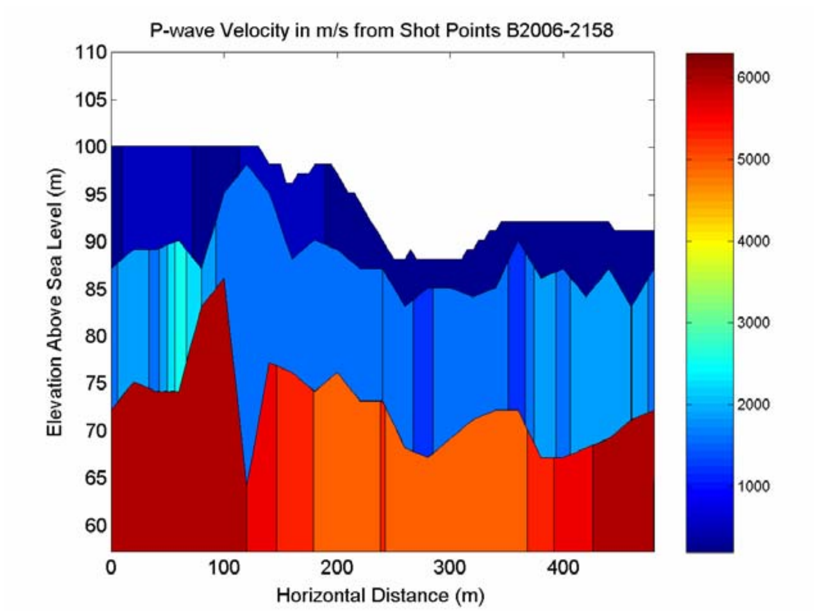

Figure 1: Section of the tomography model used to perform static corrections, showing a layer of top soil, a layer of glacial till, and the underlying schist

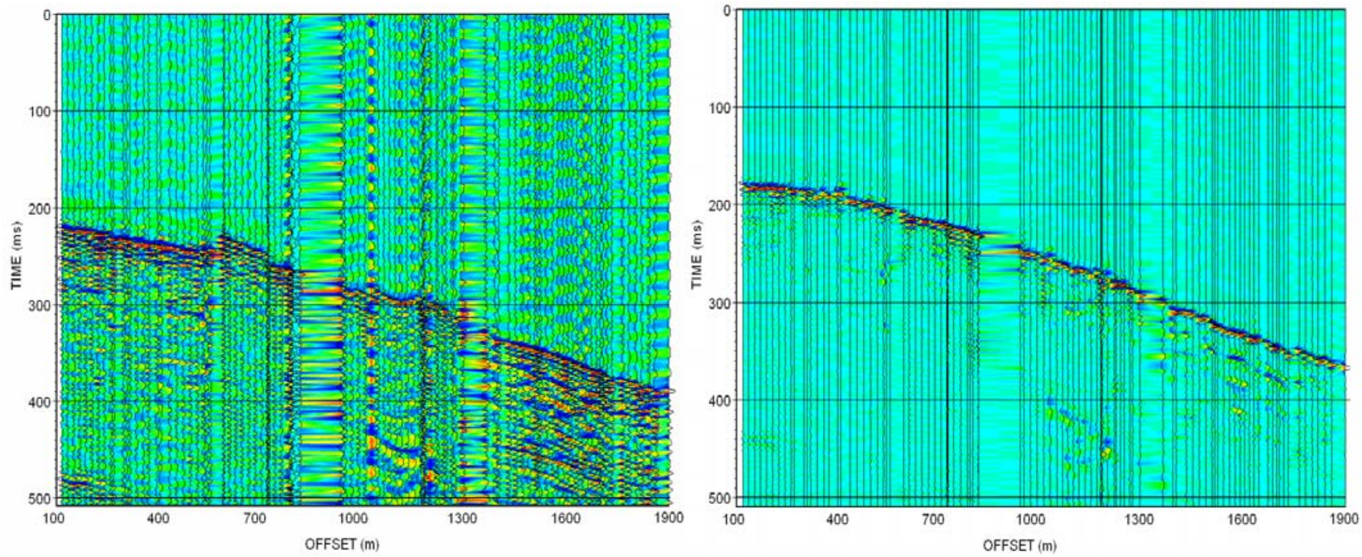

Figure 2: Seismic traces of the Northeastern 1000 m walk-away VSP, in the time-offset domain, before (left) and after static corrections and filtering to enhance the P-wave arrival (right).

After processing, a tau-p transform was used on the walk-away data set (e.g. Kebaili and Schmitt, 1997), allowing the measurement of phase (plane wave) velocity as a function of angle from vertical. These anisotropy measurements showed the anisotropy in the two azimuthal directions, to a maximum angle of ~65° from vertical (fig. 3).

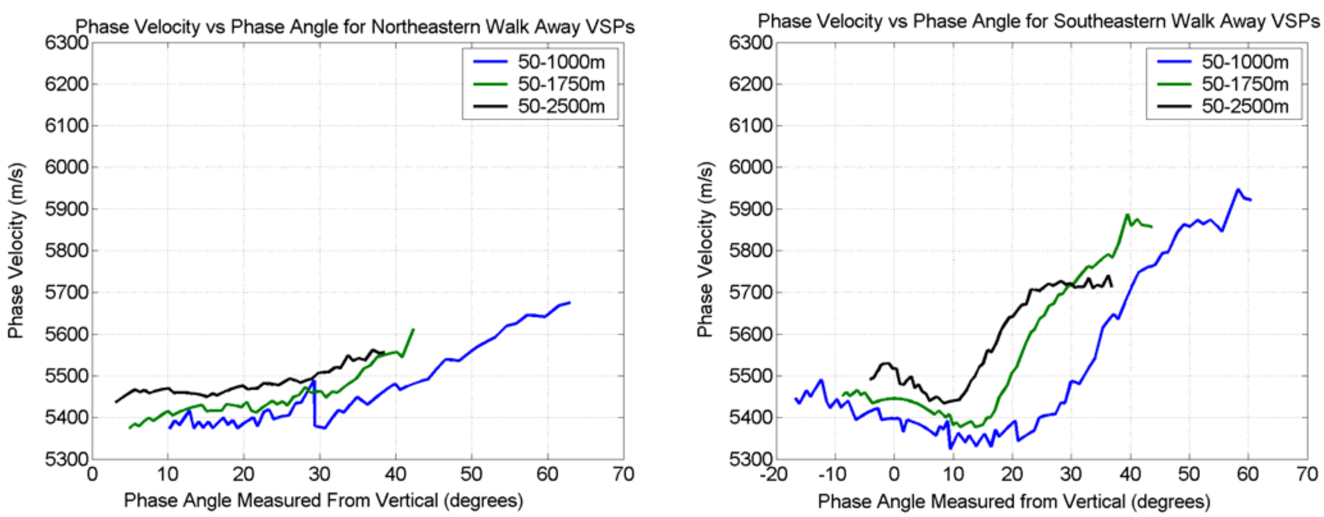

Figure 3: Phase velocity vs phase angle measurements along two different azimuths at the three different depth intervals.

Hudson’s model (1981) was used to forward model a transversely isotropic medium with fluid-filled cracks, and these theoretical results were compared with the experimental measurements of anisotropy between a depth of 50-1000 m (fig. 4). Good agreement between the theoretical and experimental measurements indicates that the theoretical model yields accurate velocity measurements for those areas where the experimental measurements are not available.

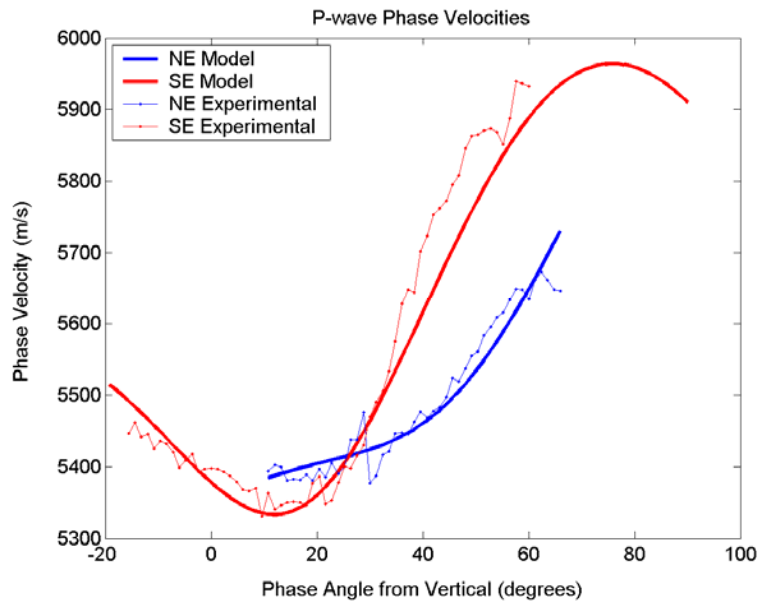

Figure 4: Experimental anisotropy results between 50-1000 m in depth along both azimuths, and the theoretical model results along the same azimuths.

Conclusions

The strongest anisotropy is observed in the 1000 and 1750 m walk-away VSPs in the Southeastern direction. Significantly less anisotropy is observed in the 2500 m walk-away VSP, most likely due to a change in geology that includes increasing amounts of pegmatitic granite. The reduced anisotropy observed in the Northeastern direction is most likely a result of the orientation of the stress fields, and therefore of the fractures present. This conclusion is confirmed through the theoretical model.

Good agreement is reached between the theoretical model and the experimental results for the P-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, perturbed with a crack density of 0.063 and the cracks aligned in a plane with strike S87°E and dip 35°. The uncracked schist shows intrinsic anisotropy, with a theoretical minimum P-wave velocity of 5650 m/s and a maximum of 6050 m/s; the addition of cracks to the schist contributes the remaining anisotropy.

Future work will include attempts to determine accurate S-wave velocities from the walk-away VSP data sets in order to further refine the theoretical model. We hope to soon obtain the corresponding borehole image logs to obtain further information on in situ fractures and their orientation for direct comparison, or inclusion into, the current seismic anisotropy model.

Acknowledgements

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