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Experimental Estimation of Compressional Velocities of a Series of Swedish Crystalline Rocks and Ores

A. Malehmir* (Uppsala University), M. Andersson (Uppsala University), M. Lebedev (Curtin University), M. Urosevic (Curtin University) & V. Mikhaltsevitch (Curtin University)

SUMMARY

More than 50 samples were collected and measured for their physical properties including P- and S-wave velocities at both atmospheric and elevated pressures using 0.5 MHz P- and S-wave transducers in a rock physics lab at Curtin University. The rock samples are geographically from two major mining camps in northern and central parts of Sweden with samples ranging from mineral deposits, volcanic rocks to deformed and metamorphosed rocks, and from a region with unique alkaline and carbonatite rocks in the north-central part of Sweden. A few of the rock samples were also measured using a low-frequency (10-50 Hz) apparatus to provide comparison with the ultrasonic velocity measurements. Using a laser interferometer device, rock samples from a major deformation zone were measured for their elastic anisotropy with preliminary results demonstrating that a major reflection zone observed from the deformation zone could be partially enhanced by anisotropy than purely by acoustic impedance contrast. Results may also indicate that some of the coarse grain massive sulphide deposits, in contrary with what generally thought, show a very little acoustic impedance contrast with their host volcanic rocks. Iron deposits show a large acoustic impedance contrast with their hostrock, making them favorable target of seismic methods.

Introduction

Borehole geophysical measurements can provide useful information on physical properties of mineralized zones, hostrocks, main lithologies and deformation zones (e.g., Salisbury et al., 2000). In particular, sonic and density logs can be correlated with surface or down-hole seismic data to explain the nature of reflections (Malehmir and Bellefleur, 2009). However, because of mainly two reasons their use in crystalline environment is limited to only areas with a current detailed exploration or even exploitation program. These are (1) lack of sufficiently deep boreholes (or economic constraints) and (2) limited types of measurements can be done in slim-holes. Reflection seismic studies and integration with different geophysical and geological data within Sweden started more than 25 years ago. It has involved research on large-scale crustal geological structures that have developed via tectonic processes, mineral prospecting, and reflection seismic surveying in connection with locating sites for nuclear waste storage. Although in Sweden numerous reflection seismic surveys have been conducted with numerous published accounts (e.g., Lund et al., 1987), a detailed, routine, and systematic measurement of seismic wave-velocity of rock samples has not yet been carried out to study rocks that produce reflections. In this paper, we present results from seismic wave-velocity measurements of a series of rock and ore samples from the Swedish crystalline upper crust with the main objectives of (i) providing information about P- and S- wave velocities of major lithologies, (ii) studying seismic response of major mineral deposits, and (iii) analysing elastic anisotropy effects of major deformation zones on the creation of observed reflections. In addition, the paper provides information about seismic velocity of some of the very important Swedish crustal rocks that are globally unique and of interest to geologists and geophysicists both nationally and internationally (i.e., the alkaline and carbonatite rocks of the Alnö ring complex).

Rock samples and their descriptions

More than 50 rock samples from mainly three regions of Sweden were collected for this study. Some of the samples are from a major massive sulphide camp of northern Sweden, known as the Skellefte Ore District, and some from a poly-metal mining camp in the central part of Sweden, known as the Bergslagen Ore District. More than 10 samples were also obtained from the Alnö complex in the north-central part of Sweden. The samples are both from drill-cores (120-700 m deep) and hand-samples taken from outcrops. Lithologically, the samples vary from felsic intrusive and extrusive rocks such as granite, rhyolite, and granodiorite to more mafic rocks such as pyroxenite, gabbro, nepheline-syenite as well as carbonatite and Alnöite. There are also samples from two major massive sulphide deposits and their hostrocks from the Skellefte Ore District and iron deposits and their hostrocks from the Bergslagen Ore District. For comparisons, we also obtained a few samples from a massive sulphide deposit in Norway and another iron orebody in northern Sweden.

Experiment

In the following subsection, we describe different methods used to measure seismic wave-velocities.

Ultrasonic measurements

Using both P- and S-wave transducers (0.5 MHz central frequency), we measured ultrasonic wave velocities of all the samples at both atmospheric and at elevated confining pressure of up to 65 MPa (equivalent of a maximum depth of 3 km). Because the samples are from crystalline environment and largely deformed and metamorphosed to high-grade faceis with very little expected porosity (<2 %), no attempt was made to saturate the samples during the measurements. Figure 1a shows ultrasonic device used for these measurements.

Low-frequency measurements

Figure 1b shows a photo of the mechanical assembly of the low-frequency apparatus. The device comprises two platforms and the arrangement of units between them. The latter includes a core holder containing a rock sample to be tested and filled with mineral oil, two plugs with fluid passages located at the both ends of the sample for fluid conveying and pore pressure control, a hydraulic pressure machine, a piezoelectric actuator adapted to be placed in contact with the tested sample, and an aluminium calibration standard. The multilayer piezoelectric adaptor transforms a periodic voltage, applied by an oscillator, into mechanical stress, which causes displacements in the aluminium standard and specimen. The displacements modulate the conductivity of the strain gauges coupled with the standard and rock sample. A set of electrical bridges (and strain gauge) transforms the modulated conductivity into electrical signals, which, after digitizing by an analogue-digital converter, are received by an acquisition computer, where the signals are averaged and processed. The processing in the acquisition computer is synchronized with the oscillator by a special triggering signal. For detailed descriptions of the method, readers are advised to see Mikhaltsevitch et al. (2010). At this stage, only one rock sample has been tested using the low-frequency apparatus device, that is the sample from an iron orebody in the Bergslagen. The seismic-wave velocities and attenuation were measured at frequencies of 10, 30 and 50 Hz and at uniaxial pressure of 10, 20 and 30 MPa.

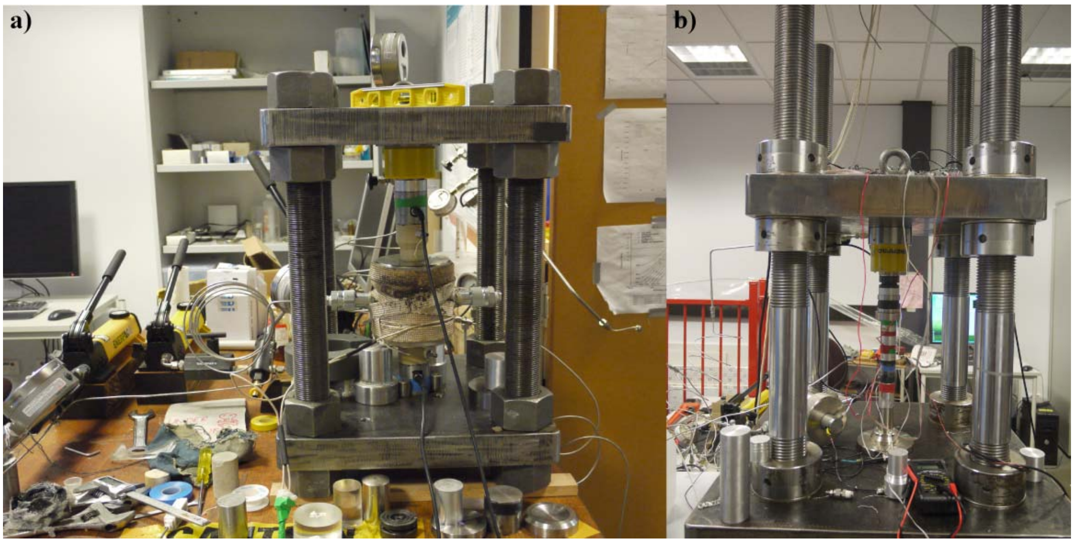

Figure 1 *(a) Ultrasonic device and (b) low-frequency apparatus used in this study to measure elastic properties and thus seismic wave-velocities.*

Elastic anisotropy estimations using laser interferometery

The main idea with the laser interferometer device is to measure time dependent displacement of a particular point on the sample surface in three independent directions (Lebedev et al., 2010). This is analogous to measuring 3-component data on the surface of a sample but using a P-wave (or S-wave) transducer (source) attached to the bottom of the sample (see Figure 2). The high accuracy of these measurements makes the determination of the polarization straightforward, and thus the identification of the wave-types less ambiguous. These measurements can be used to estimate the stiffness tensor of anisotropic rock samples. The propagation of the elastic waves within a sample is governed by the stiffness tensor and density of the material. Hence, the polarizations of these waves as well as their velocities and amplitudes depend on the stiffness tensor. Using sufficient number of measurements of the polarizations and velocities of these waves, all (up to 21) coefficients of the stiffness tensor of sample can be obtained (see Bona et al., 2008). In total, five samples from a major deformation zone in the Bergslagen were measured for their elastic anisotropy using the laser interferometer device.

Results

Figure 3a shows a graph of P-wave velocity versus density for all the measured samples using the ultrasonic device at atmospheric pressure. Figure 3b is a similar graph but obtained at an elevated pressure of 60 MPa. A comparison between the two graphs suggests that at elevated pressures most of the samples show only a slightly increase in their P-wave velocity. This can be attributed to the fact that in crystalline environment rocks show very little porosity, thus are less sensitive to applied pressure compared with samples from sedimentary environment. Coarse grain massive sulphide ores of the Skellefte District show very low seismic-wave velocity compared with the fine grain samples obtained from Norway. In contrary, iron ore samples from the Bergslagen District show higher P-wave velocity than their hostrock, making them favourable to be detected by surface seismic methods. Low-frequency measurements from the iron ore sample show a similar seismic wave-velocity compared with the ultrasonic results and show very little dispersion (see Figure 4). Although preliminary, anisotropy measurements using the laser interferometer device suggest that some of the samples from the deformation zone show up to 10 % anisotropy in their seismic wave-velocity. Further work is currently going on to better understand the nature of anisotropy in these samples and calculate their stiffness tensors.

Figure 2 (a) Laser interferometer device and (b) an example of sample set-up used to study anisotropic nature of some of the samples taken from a major deformation zone.

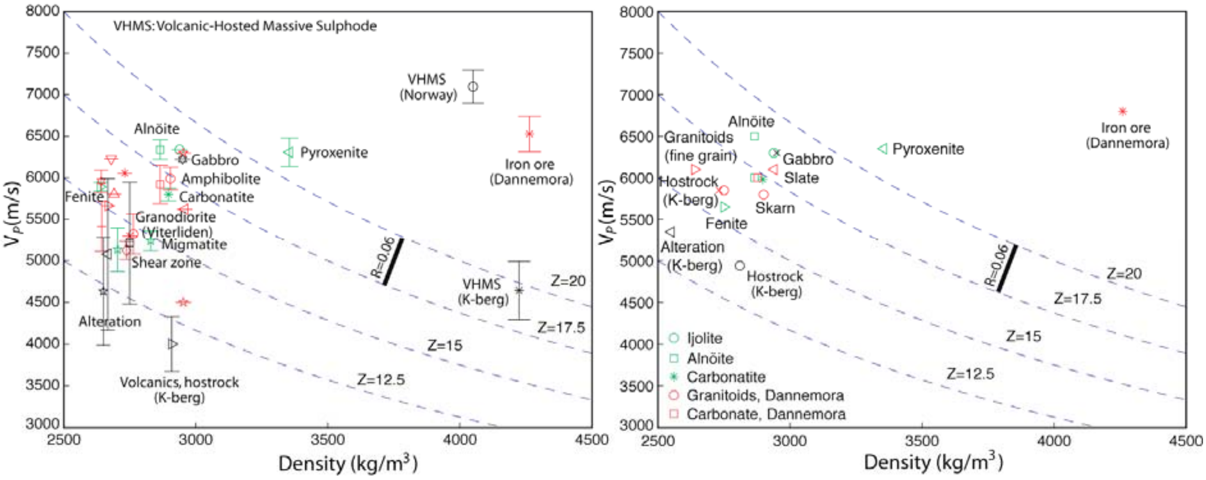

Figure 3 P-wave seismic velocities versus density graphs obtained using the ultrasonic device for (a) atmospheric pressure and (b) confining pressure of 60 MPa.

Comparison with field seismic observations

Figure 5 show a migrated seismic section from a seismic reflection survey recently acquired over the deformation zone and an iron ore east of it in the Bergslagen District. The seismic data clearly show seismic signature of the deformation zone and the iron ore further supporting our measurements that the iron ores have significant acoustic impedance contrast with their hostrock in the site as well as that the deformation zone is partly reflective due to its elastic anisotropic nature. Further work is currently being conducted to simulate the seismic response of the deformation zone using finite-difference algorithms accounting for their anisotropic nature in the simulation.

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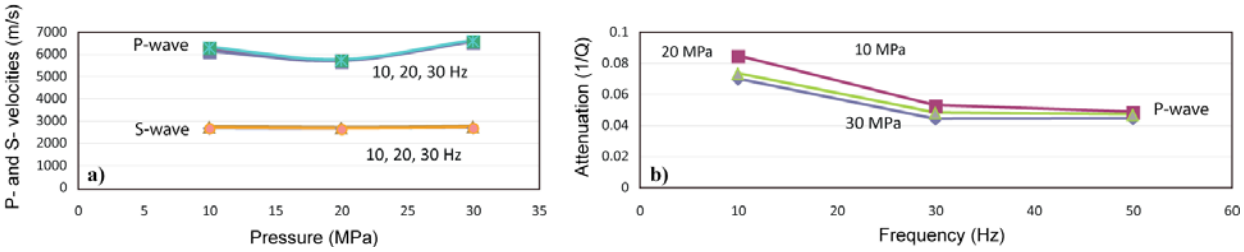

Figure 4 P- and S-wave seismic velocities obtained using the low-frequency apparatus at frequencies of 10, 30, and 50Hz.

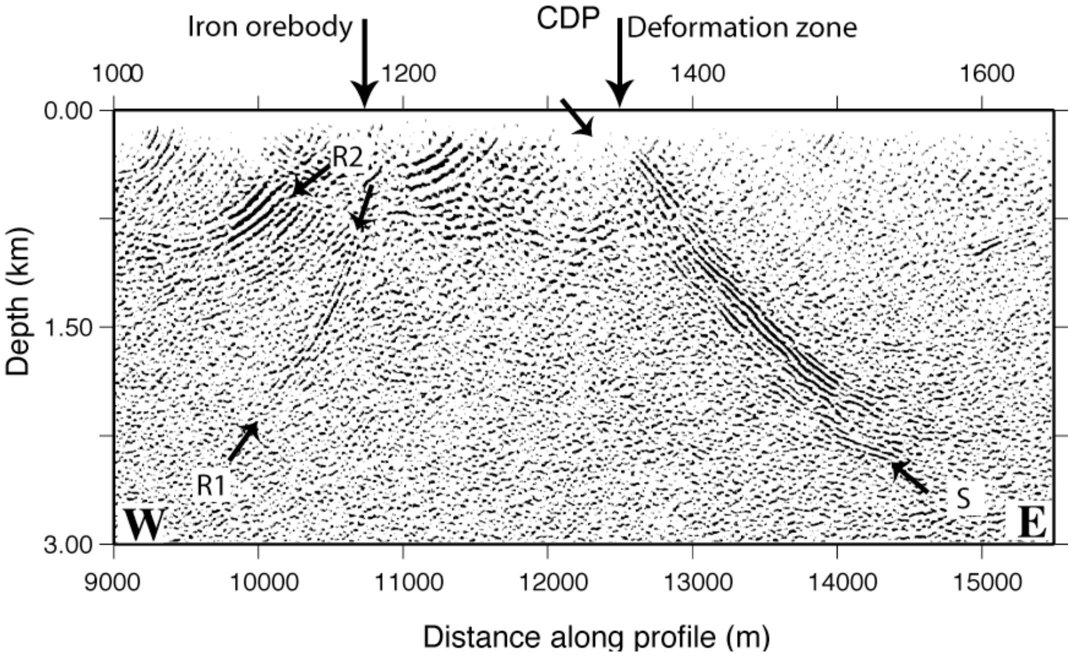

Figure 5 Migrated seismic section along a portion of the seismic profile acquired over a major deformation zone and an iron orebody in the Bergslagen Ore District (Malehmir et al., 2011; submitted).

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