Full Waveform Acoustic Logging Applications in Mineral Exploration and Mining

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INTRODUCTION

Since 1993, the Geological Survey of Canada (GSC) has acquired full waveform acoustic logs to demonstrate applications of acoustic logging to mining and mineral exploration. Boreholes logged were from mining areas across Canada, including Sudbury, Timmins, Val d'Or, Matagami, Chibougamau, Bathurst and Myra Falls. Full waveform acoustic probes record the complete acoustic signal from a transmitter on the probe at two (or more) receivers located at different distances from the transmitter. By recording the full acoustic waveform, logs of the velocities and amplitudes of different arrivals (e.g., P-wave, S-wave, tube wave) can be extracted from the data. The complete waveform from a single receiver can also be displayed as a variable density log. Four examples show how these data can be used in lithologic mapping, ore delineation, detection and characterization of permeable zones and the interpretation of seismic reflection and tomography surveys.

LITHOLOGIC MAPPING: THE CORNER BAY DEPOSIT

The Corner Bay copper deposit is located in the Chibougamau-Matagami greenstone belt near the town of Chibougamau, Québec. In 1994, the GSC acquired borehole geophysical logs, including full waveform acoustic, in one hole in the Corner Bay deposit to document the geophysical signature of the deposit (Pflug and Killeen, 1997). The P-wave velocity log for the upper 300 m of this hole is shown in Figure 1. The P-wave velocity correlates well with the lithology in this hole. The gabbroic anorthosite, meladiorite, melanocratic gabbro and fractured and altered zone are characterized by higher velocities (6.5-6.7 km/s), whereas the intermediate porphyry and sheared and altered zone are characterized by lower velocities (5.8-6.1 km/s). According to the velocity log (and gamma ray log, not shown), the zone from 243 m to 246 m may not be sheared and altered as indicated on the geological log.

ORE DELINEATION: THE MCCONNELL DEPOSIT

The McConnell nickel deposit occurs in the Sudbury basin of Ontario. It is a massive sulphide body consisting primarily of pyrrhotite and pentlandite and is representative of Sudbury-type nickel deposits (Mwenifumbo *et al.,* 1993). In 1993, the GSC acquired full waveform acoustic logs in one hole at the McConnell deposit as part of a project to document the geophysical signatures of major deposit types in Ontario (Pflug *et al.,* 1994; Killeen *et al.,* 1993, 1995). The P-wave velocity log from the McConnell deposit, shown in Figure 2, is an excellent example of the use of acoustic logs in ore delineation. The anomalously low average velocity of the massive sulphide zone between 136 m and 152 m (4.4 km/s) contrasts sharply with the average velocities of the enclosing rocks (5.9 km/s to 6.4 km/s).

FRACTURE DETECTION: THE BELL ALLARD DEPOSIT

Full waveform acoustic logging is an important technique for in situ fracture characterization and permeability estimation (Paillet and Cheng, 1991). Open fractures intersecting a borehole disrupt the propagation of acoustic energy along the borehole and result in a reduction in the amplitude of all arrivals in the full waveform. The amplitude of the tube wave, which propagates down the borehole at slightly less than the P-wave velocity of the borehole fluid, is found to correlate best with fracture permeability (Paillet and Cheng, 1991). In Figure 3, the P-wave velocity, tube wave amplitude, temperature gradient and variable density logs are shown for a section of a hole in the Bell Allard deposit near Matagami, Québec. The fault (206.8–209.7 m) and fault zone (287.3–291.7 m) are clearly evident on the leftmost two logs as zones of low P-wave velocity and tube wave amplitude. The greater attenuation of tube wave energy by the fault at 208 m than by the fault zone at 289 m suggests that the fault at 208 m is more permeable. Temperature gradient

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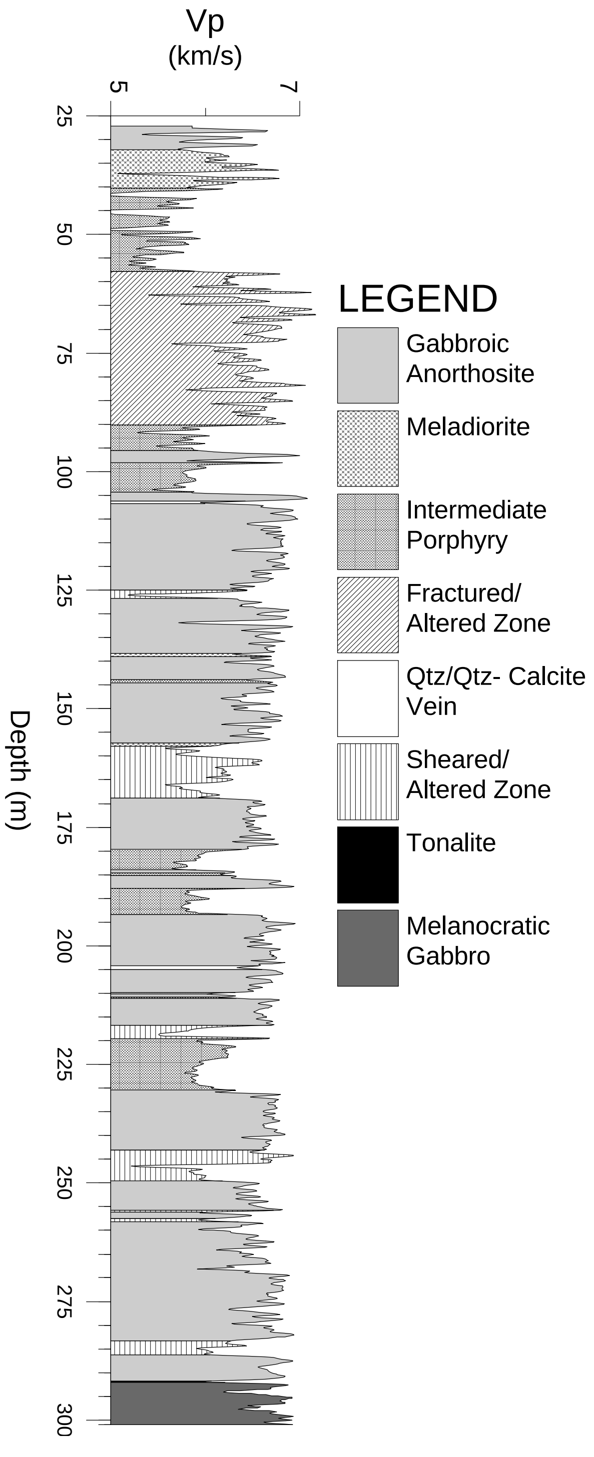

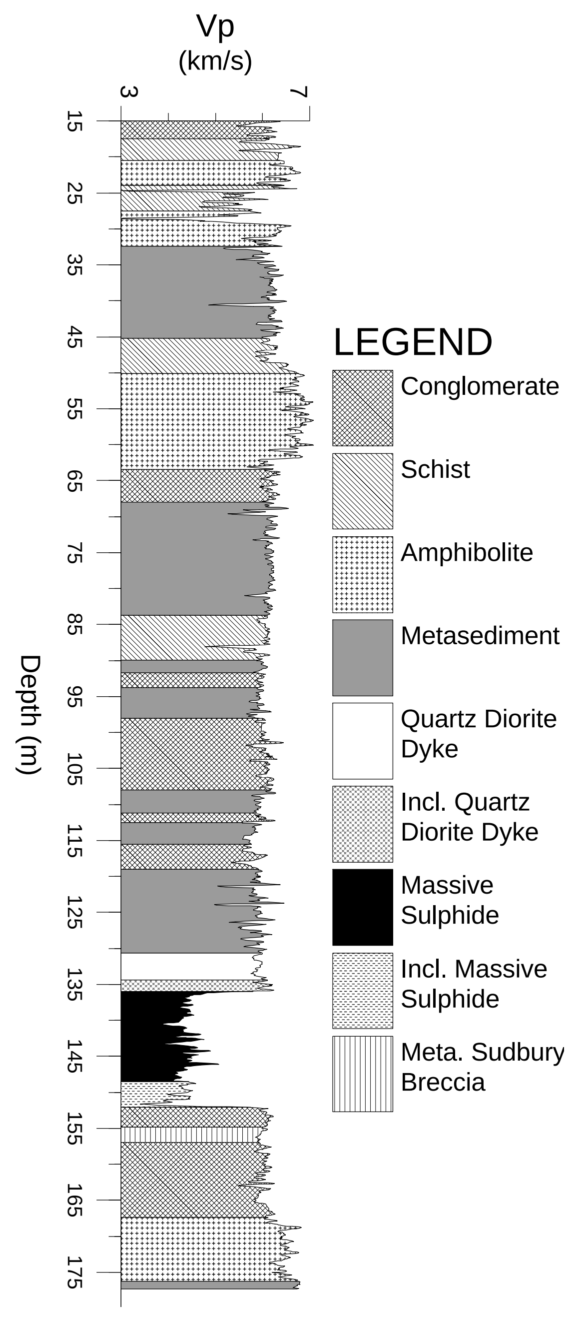

Figure 1: *P-wave velocity (Vp) log from the Corner Bay copper deposit. The excellent correlation between velocity and lithology in this hole shows how the Vp log can be used to aid in lithologic mapping.*

Figure 2: *P-wave velocity (Vp) log from the McConnell nickel deposit. The massive sulphide zone is delineated by its anomalously low velocity compared to the enclosing rocks.*

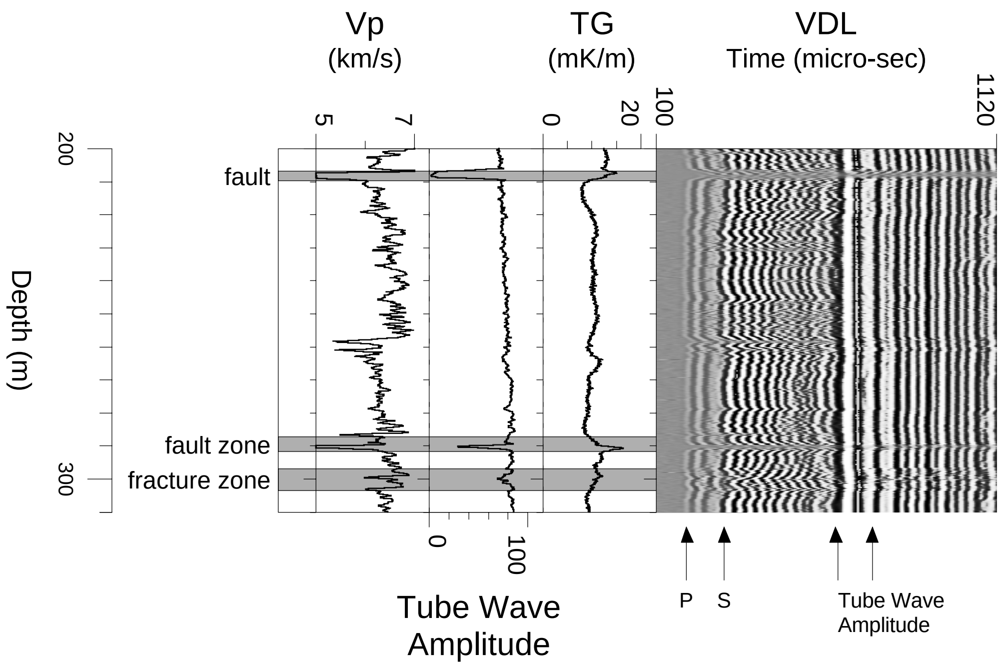

Figure 3: *P-wave velocity (Vp), tube wave amplitude, temperature gradient (TG) and variable density (VDL) logs from the Bell Allard zinc-copper deposit. The VDL is a method of displaying the full acoustic waveform at a single receiver with different wave amplitudes represented by different shades of gray. The approximate start of the P- and S-waves are indicated on the VDL. The tube wave amplitude is the root-mean-square of the waveform amplitude in the window indicated on the VDL. The fault and fault zone are evident on all four logs.*

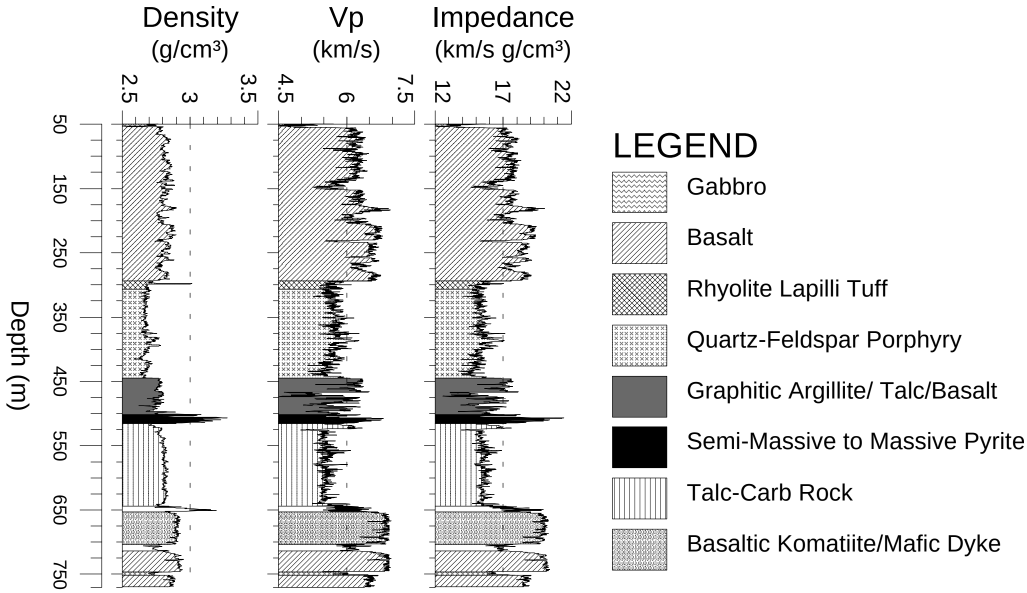

Figure 4: *Density, P-wave velocity (Vp) and acoustic impedance logs from the Kidd Creek copper-zinc mine. Acoustic impedance contrasts associated with changes in lithology indicate contacts that would cause seismic reflections. The pyrite-rich zone (505–515 m) would be visible using seismic reflection methods. (Note: The density in the pyrite-rich zone is slightly underestimated by the density log.)*

anomalies associated with the fault and fault zone suggest water flow to or from the borehole at these depths, which further confirms that these are permeable zones. The fracture zone from 296.9 m to 303.6 m appears to be less permeable than the faults based on the tube wave amplitude and variable density logs. The geological log indicates that this zone contains quartz- and calcite-filled fractures and small faults, thus reducing its permeability.

INTERPRETATION OF SEISMIC REFLECTION AND TOMOGRAPHIC SURVEYS

Recent research (Salisbury *et al.,* 1996; Milkereit *et al.,* 1996; Eaton *et al.,* 1996) has shown that seismic reflection techniques can be used to image massive sulphide mineral deposits. Interpretation of seismic reflection data requires a knowledge of the acoustic impedances (density × velocity) of the rocks, which can be obtained, in situ, from density and acoustic velocity logs. Seismic reflections occur when there is a change in acoustic impedance. In 1993, the GSC recorded density and P-wave velocity logs (Figure 4) in a hole near the Kidd Creek mine, Timmins, Ontario, as part of a project to document the geophysical signatures of major deposit types in Ontario (Killeen *et al.,* 1993). Impedance contrasts associated with changes in lithology can be seen on the acoustic impedance log (Figure 4) at several depths. In particular, the semi-massive to massive pyrite between 505 m and 515 m has a higher impedance than the rocks above and below it, which should make it visible with seismic techniques. The data shown in Figure 4 have been used by Eaton *et al.* (1996) to interpret vertical seismic profile data acquired in the Kidd Creek mine area.

Acoustic velocity logs have also been used to help interpret seismic tomography data. In 1994, the GSC acquired velocity logs in three holes at the Louvicourt mine, near Val d'Or, Québec, for Noranda Technology Centre (NTC). The P-wave velocity data were found to correlate with iron and pyrite content and this information was used to help interpret cross-hole seismic data acquired at the mine by NTC (McCreary and Wänstedt, 1995).

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REFERENCES

Eaton, D., Guest, S., Milkereit, B., Bleeker, W., Crick, D., Schmitt, D. and Salisbury, M., 1996, Seismic imaging of massive sulfide deposits: part III. Borehole seismic imaging of near-vertical structures: Economic Geology, **91**, 835-840.

Killeen, P.G., Elliott, B.E. and Mwenifumbo, C.J., 1993, Ore deposit signatures and borehole geophysics test sites in Ontario: Proceedings of the 5th International Symposium on Geophysics for Minerals, Geotechnical and Environmental Applications, paper G.

Killeen, P.G., Mwenifumbo, C.J. and Elliott, B.E., 1995, Mineral deposit signatures by borehole geophysics: Data from the borehole geophysics test site at the McConnell nickel deposit (Garson Offset), Ontario, Geol. Survey of Canada, Open File 2811.

McCreary, R.G. and Wänstedt, S., 1995, Applications of multivariate statistics and pattern recognition to geophysical logging at Noranda: Proceedings of the 6th International Symposium on Borehole Geophysics for Minerals, Geotechnical and Groundwater Applications, paper G.

Milkereit, B., Eaton, D., Wu, J., Perron, G., Salisbury, M., Berrer, E.K. and Morrison, G., 1996, Seismic imaging of massive sulfide deposits: part II. Reflection seismic profiling: Economic Geology, **91**, 829-834.

Mwenifumbo, C.J., Killeen, P.G., Elliott, B.E. and Pflug, K.A.,1993, The borehole geophysical signature of the McConnell nickel deposit, Sudbury area: Proceedings of the 5th International Symposium on Geophysics for Minerals, Geotechnical and Environmental Applications, paper I.

Paillet, F.L. and Cheng, C.H., 1991, Acoustic Waves in Boreholes: CRC Press Inc.

Pflug, K.A., Killeen, P.G. and Mwenifumbo, C.J., 1994, Acoustic velocity logging at the McConnell nickel deposit, Sudbury area, Ontario: preliminary in situ measurements: Current Research 1994-C, Geol. Survey of Canada, 279-286.

Pflug, K.A. and Killeen, P.G., 1997, Borehole geophysical logs at the Corner Bay copper deposit, Chibougamau area, Québec: Geol. Survey of Canada, Open File 3388.

Salisbury, M., Milkereit, B. and Bleeker, W., 1996, Seismic imaging of massive sulfide deposits: part I. Rock properties: Economic Geology, **91**, 821-828.