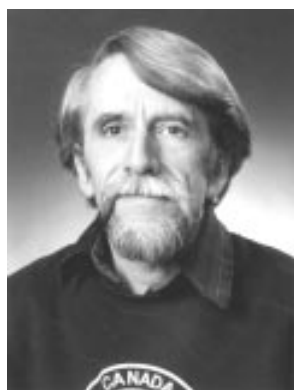
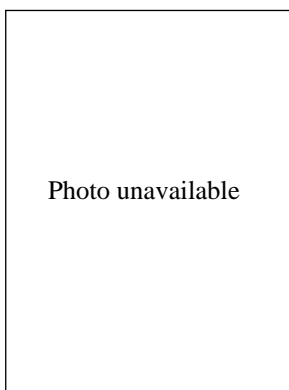


## Seismic Prospecting for Massive Sulphides

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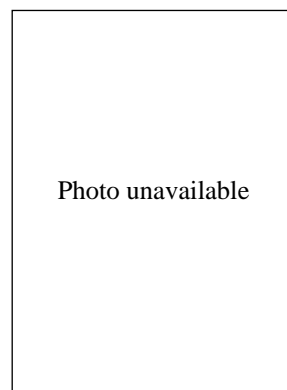
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### Abstract

Laboratory and logging measurements of the density and compressional wave velocity ( $V_p$ ) of ore and host rock samples from massive sulphide deposits show that sulphides have significantly higher acoustic impedances at elevated pressures than their mafic or felsic hosts. This suggests that it should be possible to detect and delineate large massive sulphide deposits using high resolution seismic reflection techniques. This prediction has been confirmed in recent seismic tests in which a massive sulphide body was detected near the giant Kidd Creek deposit using side-scan imaging techniques.

### Introduction

The Canadian mining industry has traditionally relied on mapping, drilling and potential field techniques to locate shallow base metal deposits, but with the known domestic reserves of copper (Cu) and zinc (Zn) declining, there is increasing recognition that new deep exploration techniques must be used if the industry is to remain

profitable in the long term. A promising new approach is to search for base metal deposits using high resolution seismic reflection techniques similar to those employed for exploration by the petroleum industry, but modified for the hard rock environment. Over the past three years, the Geological Survey of Canada, in collaboration with INCO, Noranda Mining and Exploration, and Falconbridge, Ltd., has engaged in an extensive directed research

program involving laboratory and borehole physical property measurements, seismic modelling and field tests over deposits in the Sudbury, Bathurst, Kidd Creek and Matagami mining camps, to determine if seismic techniques can be used for the direct detection of massive sulphides. The initial results from this program, presented here using data from Kidd Creek as an example, strongly suggest that the answer is yes.

Lithology	n	Density (g/cc)	$V_p$ (km/s)	Acoustic Impedance
Basalt	6	2.91	6.68	19.4
Diorite/ Gabbro	3	2.99	6.83	20.4
Ultramafics (talca)	3	2.92	6.06	17.7
Rhyolite	5	2.71	6.11	16.6
Argillite	3	2.75	6.02	16.6
Massive sulphides	11	4.11	6.19	25.4

Compressional wave velocities ( $V_p$ ) at 200 MPa.

Table 1: Mean acoustic properties of North Rhyolite lithologies based on laboratory data

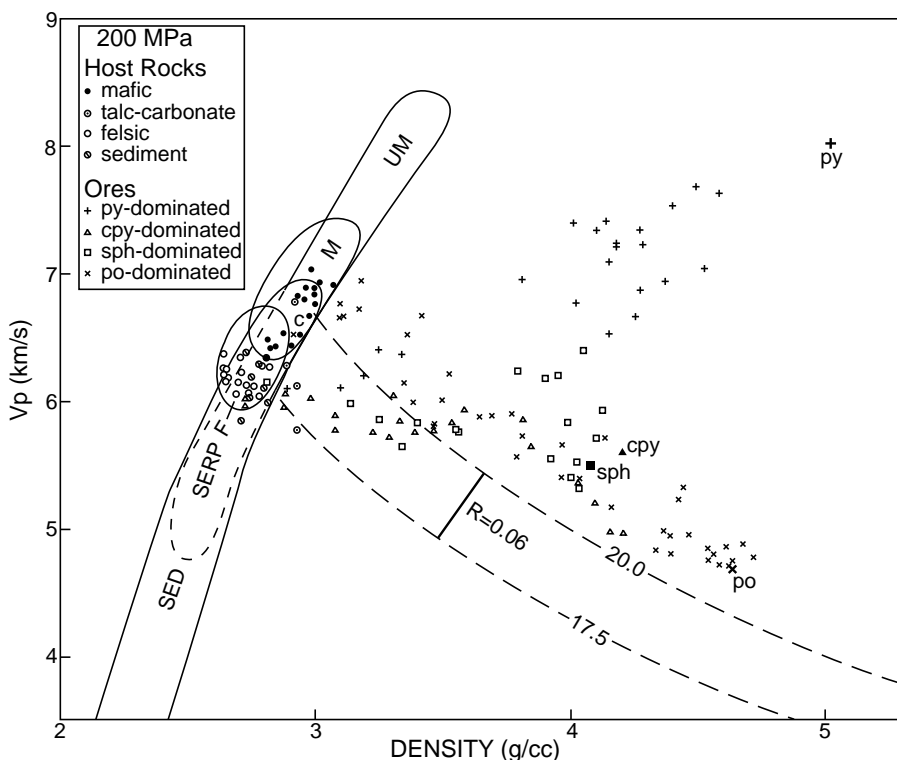


Figure 1: Compressional wave velocities ( $V_p$ ) versus densities for sulphide ores and host rocks at a confining pressure of 200 MPa. Ores coded by predominant sulphide: py, pyrite; cpy, chalcopyrite; sph, sphalerite; po, pyrrhotite (end-members in bold). Subfields along Nafe-Drake curve: SED, sediments, including carbonates (c); SERP, serpentine; F, felsic; M, mafic; UM, ultramafic. Also shown are lines of constant acoustic impedance for felsic ( $Z=17.5$ ) and mafic (20) rocks and the reflection coefficient required to make a strong reflection ( $R=0.06$ ).

### Conditions for Reflection

In principle, an ore body should be seismically detectable if three conditions are met:

**Condition 1)** The acoustic impedance ( $Z$ ) or velocity-density product of the ore must be sufficiently greater than that of the host rock to produce a reflection coefficient,  $R > 0.06$ , where  $R$  is defined by the relation,

$$R = \frac{Z_o - Z_h}{Z_o + Z_h}$$

and  $Z_o$  and  $Z_h$  are the ore and host rock impedances, respectively. Since the impedances of massive sulphides have never been systematically investigated, we measured the densities and compressional wave velocities ( $V_p$ ) of a large suite of ore and host rock samples of known composition from Sudbury, Kidd Creek and Les Mines Selbaie to a confining pressure of 600 MPa using the pulse transmission technique of Birch (1960). The results, presented at a standard reference pressure of 200 MPa in

Figure 1, show that silicate host rocks generally fall within the mafic (M) and felsic (F) fields of the Nafe-Drake curve (Ludwig *et al.* 1971), but that massive sulphides lie far to the right in a large velocity-density field controlled by the end-member properties of pyrite, pyrrhotite, sphalerite and chalcopyrite (Salisbury *et al.* 1996). Close inspection of the data shows that the sulphide field can be divided in overlapping subfields (Fig. 2) in which the acoustic properties are controlled by mixing lines connecting matrix and end-member properties. Thus for example, density increases linearly with modal pyrite content in rocks composed of pyrite and felsic gangue, and  $V_p$  increases along a trend consistent with the time-averaging relationship of Wyllie *et al.* (1958).

If lines of constant impedance are superimposed on the velocity-density data as in Figure 1, it can be seen that sulphide ores have higher acoustic impedances than most common felsic or mafic hosts and that the impedance contrast increases rapidly with

pyrite content. As a rule of thumb, a contrast of 2.5 (the contrast between felsic and mafic rocks) is sufficient to give a strong reflection ( $R=0.06$ ). Thus massive sulphides of any composition should make strong brilliant reflectors in a felsic setting and sulphides with an admixture of pyrite should do so in either a felsic or a mafic setting.

**Condition 2)** The orebody must be large enough to detect using seismic methods. Under ideal conditions, a body with a diameter of one wavelength can be detected as a point source or scatterer (Berryhill 1977) but in practical terms, the smallest deposit that can be resolved as a planar body at a given depth,  $z$ , must have a minimum diameter,  $d$ , equal to that of the first Fresnel zone,

$$d = (2zv/f)^{1/2}$$

where  $v$  is the average formation velocity and  $f$  is the dominant frequency (Yilmaz 1987). Similarly, the body must be at least 1/4 wavelength thick for its thickness to be resolved (Widess 1973). Thus assuming a formation velocity of 6 km/s, a body which is 60 m across by 15 m thick could be detected as a point source at a depth of 1 km using a seismic frequency of 100 Hz, while a body 350 m across at the same depth could be resolved as a planar reflector.

**Condition 3)** Finally, the geometry of the body must allow reflected energy to return to the receivers. While shallow-dipping bodies will reflect energy back to the surface, steeply-dipping bodies will shed

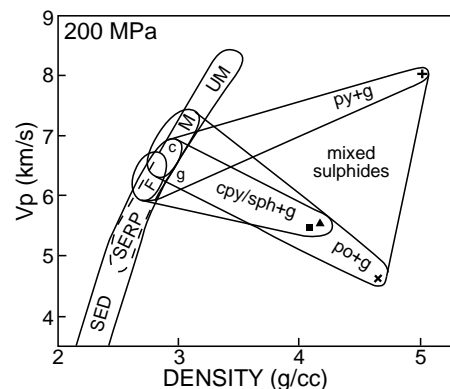


Figure 2: Velocity ( $V_p$ ) - density fields for common sulphide ores and silicate host rocks; g, gangue; other abbreviations as in Figure 1.

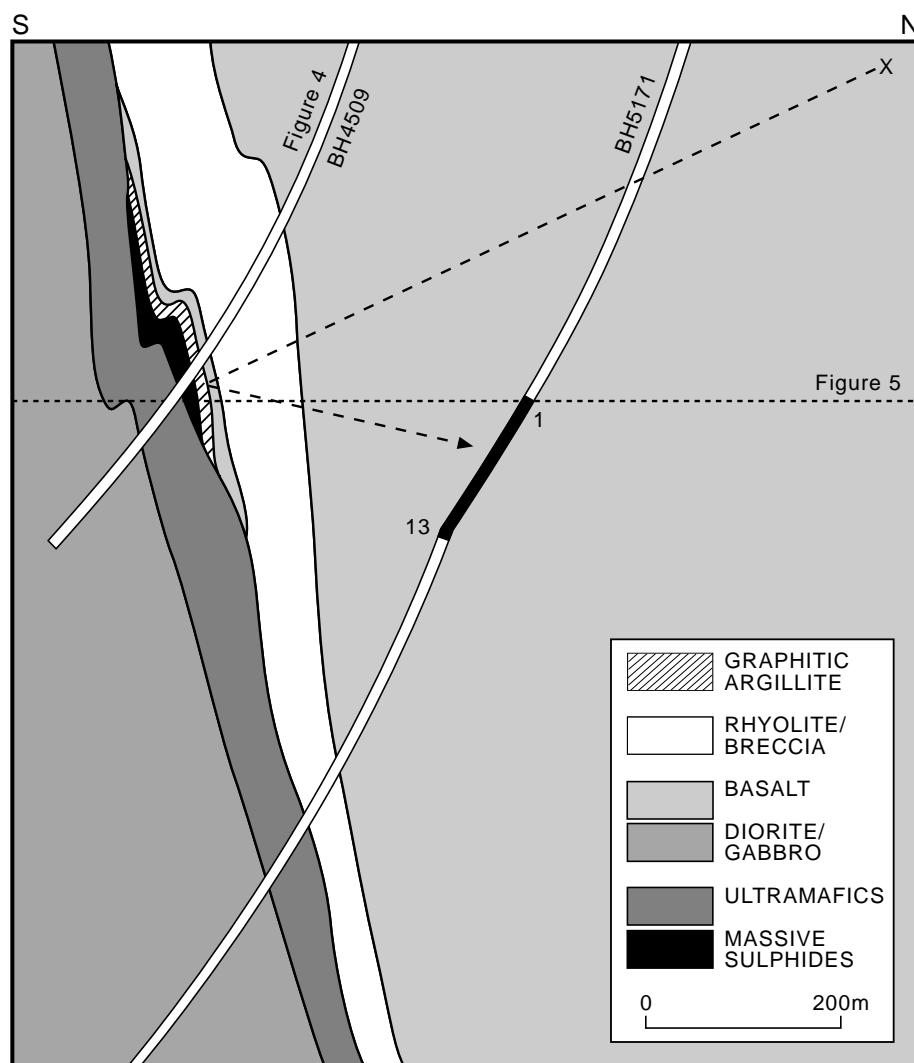


Figure 3: N-S section through the North Rhyolite showing location of orebody. Logs shown in Figure 4 were obtained in borehole BH 4509. The seismic experiment was conducted in borehole BH 5171 with the seismometer occupying 13 stations immediately below the horizontal image plane at 350 m shown in Figure 5 and the shots were fired in an E-W arc which intersects the section at X.

most reflected energy downward (Milkereit *et al.* 1996). In practice, if the dip exceeds  $60^\circ$ , the optimum detection strategy will be to use borehole seismic techniques which place the receivers below the reflection point (Eaton *et al.* 1996).

In summary, it is apparent that while massive sulphide deposits commonly meet the conditions required for reflection, in hard rock terrains, they will often be small, brilliant, steeply-dipping reflectors rather than the continuous, shallow-dipping reflectors commonly imaged by the petroleum industry. Their detection will often require novel acquisition geometries, customized computer processing and a thor-

ough understanding of their acoustic properties.

### Field Tests at Kidd Creek

Convincing tests of this technique have recently been conducted by the Geological Survey of Canada at several mine sites in Canada, including the giant Kidd Creek Cu-Zn deposit near Timmins, Ontario. The tests consisted of laboratory measurements of density and velocity on an extensive suite of samples representing the major lithologies encountered in the camp, followed by logging and borehole seismic studies in the vicinity of a steeply-dipping orebody in the North Rhyolite which had been delineated but never mined (Fig. 3). The laboratory

results, summarized in Table 1 for the lithologies present in the vicinity of the seismic test, show that large impedance contrasts exist between the felsic and mafic lithologies and between the sulphides and all host rock lithologies. Interestingly, the ultramafics in this locality behave like felsic rocks because they have been altered to talc which has a low velocity and thus a low impedance. If the reflection coefficients between all possible pairs of these lithologies are calculated from Equation 1 using the impedances presented in Table 1, it is clear that strong reflections are to be expected between mafic and felsic units, ultramafic rocks and diorite or gabbro and between the sulphides and any of the other lithologies in the area (Table 2).

While the laboratory results suggest that the ores should be strong reflectors, it is important before conducting seismic field tests, to determine if the impedance contrasts calculated from laboratory data are consistent with in situ data and if they persist at seismic scales of investigation. To this end, an 840 m borehole (BH 4509 in Fig. 3) which intersects all of the major lithologies in the North Rhyolite, was continuously logged with compressional wave velocity and density tools and an impedance log was calculated from the resulting velocity and density data. The results, presented in Figure 4 along with reflection coefficients calculated from the impedance log at key lithologic contacts, show that the impedance contrasts measured in the lab are consistent with in situ values, after corrections have been made for differences in pressure, and that these contrasts persist at formation scales.

Finally, an *in situ* seismic test was conducted to determine if the North Rhyolite deposit could be directly imaged. Since the orebody is steeply dipping (Fig. 3), the test was conducted using a modified vertical seismic profiling (VSP) shot-receiver configuration in which the seismometer was placed in a deep borehole (BH 5171) subparallel to, but below, the hole which was logged, thus allowing the receivers to detect energy reflected off the orebody from surface shots. In a conventional VSP survey, a vertical plane passing through the shot point, the VSP hole and the orebody would be imaged by shoot-

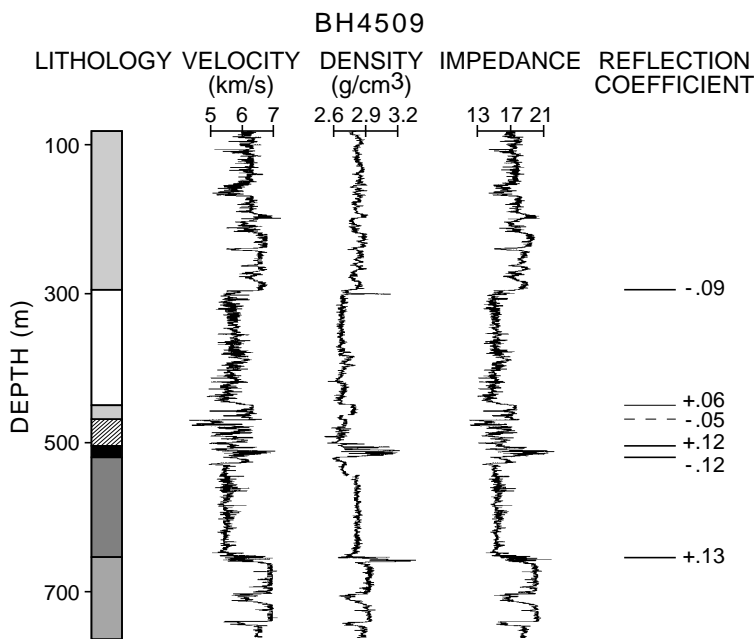


Figure 4: P-wave velocity and density logs versus depth and lithology in hole BH 4509 (lithologies as in Figure 3). Also shown are calculated impedance log and reflection coefficients at key lithologic contacts.

ing repeatedly from the same shotpoint (X) while raising the seismometer in steps from the bottom of the hole to the surface. In the present experiment, however, we imaged a horizontal plane about 350 m below the surface by restricting the receiver positions to 13 levels between 477-642 m downhole and shooting to each receiver level from 83 shallow drillholes located in an E-W arc to the north of the drillhole (Fig. 5a). By this means, the reflection points

were effectively confined to the 350 m level and the level was acoustically swept in the horizontal plane using the receivers as a fulcrum. The resulting side-scan imaging data, processed using fairly conventional VSP processing techniques (Hardage 1985) and transformed into geometric coordinates, is presented in Figure 5b for comparison with the geology determined at the 350 m level by drilling (Fig. 5a). As can be seen in this figure, the reflection results

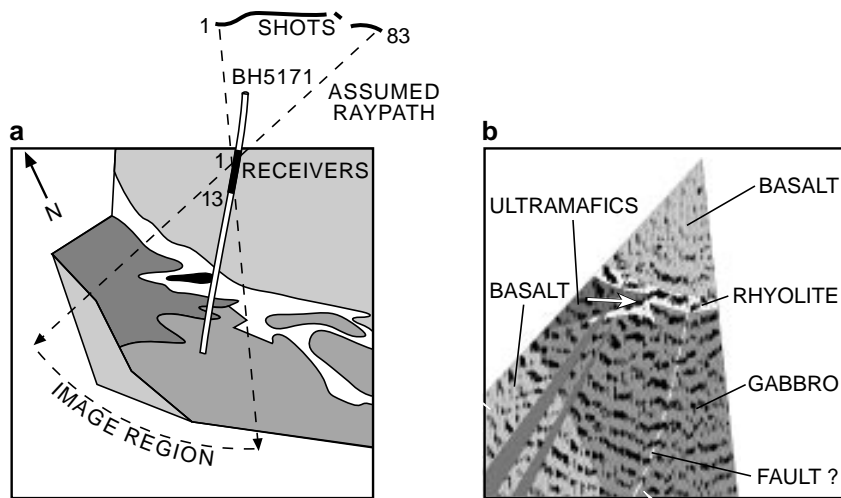


Figure 5: a) Geology at 350 m level in the North Rhyolite showing 1x1 km region imaged by borehole seismic experiment. Vertical section shown in Figure 3 is subparallel to surface projection of BH 5171. Symbols as in Figure 3. b) Corresponding seismic image showing strong reflections at basalt/ rhyolite and rhyolite/ gabbro contacts. White arrow shows location of sulphide reflection.

are in good agreement with the predictions of both the laboratory and logging studies and the known geology at the 350 m level. In particular, the basalt/ rhyolite and rhyolite/ gabbro contacts are strong reflectors and the strongest reflection in the seismic record (white arrow) is coincident with the massive sulphide deposit.

### Conclusions

From the results presented above, it is clear that massive sulphide deposits can be directly imaged using high resolution seismic reflection techniques if the ore/ host rock impedance contrasts are sufficiently large and the deposits meet the geometric constraints required for detection. Since large massive sulphide deposits often meet these constraints, we conclude that seismic reflection can be used as a deep exploration tool for base metal deposits in hard rock terrains.

### Acknowledgements

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	Basalt	Diorite/ Gabbro	Ultramafics	Rhyolite	Argillite	Sulphides
Sulphides	.13	.11	.18	.21	.21	---
Argillite	.08	.10	.03	.00	---	
Rhyolite	.08	.10	.03	---		
Ultramafics	.05	.07	---			
Diorite/ Gabbro	.03	---				
Basalt	---					

Reflection coefficients based on impedances in Table 1. Coefficients >0.06 should cause strong reflections

Table 2: Reflection coefficients between North Rhyolite lithologies based on laboratory data

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