Physical properties and seismic imaging of massive sulfides


ABSTRACT

Laboratory studies show that the acoustic impedances of massive sulfides can be predicted from the physical properties (V_p, density) and modal abundances of common sulfide minerals using simple mixing relations. Most sulfides have significantly higher impedances than silicate rocks, implying that seismic reflection techniques can be used directly for base metals exploration, provided the deposits meet the geometric constraints required for detection. To test this concept, a series of 1-, 2-, and 3-D seismic experiments were conducted to image known ore bodies in central and eastern Canada. In one recent test, conducted at the Halfmile Lake copper-nickel deposit in the Bathurst camp, laboratory measurements on representative samples of ore and country rock demonstrated that the ores should make strong reflectors at the site, while velocity and density logging confirmed that these reflectors should persist at formation scales. These predictions have been confirmed by the detection of strong reflections from the deposit using vertical seismic profiling and 2-D multichannel seismic imaging techniques.

INTRODUCTION

In the early 1900s, the petroleum industry relied on surface mapping, potential field techniques, and wildcat drilling for exploration purposes, much as the mining industry still does today. Following the initial tests of the seismic reflection method by Karcher more than 75 years ago, however, and a string of oil discoveries during the first commercial reflection surveys several years later, the exploration methods employed by the two industries rapidly diverged. Within a decade, reflection seismology had become the principal exploration tool of the petroleum industry, a position maintained to the present day through spectacular advances in acquisition, processing, and imaging technology (see Weatherby, 1940, and Enachescu, 1993, for review).

Despite the remarkable success of the seismic reflection method, the mining industry has been reluctant to embrace this technology because, until recently, its needs could be met by traditional methods. With the known shallow reserves of copper and zinc declining, however, it has become obvious that new deep exploration tools must be developed if the industry is to remain viable in the future (Debicki, 1996). Given the overall similarity of the exploration problems faced by the two industries, it is appropriate to ask whether or not this sophisticated technology might also be used for the direct detection of massive sulfides.

Although no single relationship can be used to predict the resolution of seismic reflection techniques, it should be possible to image a sulfide deposit using seismic reflection if three general conditions are met:

1) The difference in acoustic impedance between the ore and the country rock must be sufficiently large to produce strong reflections. If Z_o and Z_c are the acoustic impedances, or velocity-density products, of the ore and country rock respectively, the reflection coefficient R (the...
ratio of reflected to incident energy) can be calculated for the case of vertical incidence from the relation,

\[ R = \frac{Z_o - Z_c}{Z_o + Z_c} \]  

(1)

In practice, an impedance difference of 2.5 × 10^4 g/cm^2 s (the contrast between mafic and felsic rocks) gives rise to a value of \( R = 0.06 \), the minimum value required to produce a strong reflection in most geologic settings.

2) To be imaged as a planar reflecting surface, the body must have a diameter which is greater than the width of the first Fresnel zone, \( d_F \), defined from the relation

\[ d_F = (2zv/f)^{1/2} \]  

(2)

where \( z \) is the depth of the deposit, \( v \) is the average formation velocity, and \( f \) is the dominant frequency used in the survey. Smaller deposits with a diameter equal to one wavelength can be detected as point sources, but not imaged. Since amplitudes are severely attenuated for bodies which are less than one wavelength across (Berryhill, 1977), the diameter of the smallest body which can be detected in practice, \( d_{\text{min}} \), is

\[ d_{\text{min}} = v/f. \]  

(3)

3) The minimum thickness, \( t_{\text{min}} \), that can be resolved using seismic reflection can be estimated from the quarter wavelength criterion,

\[ t_{\text{min}} = v/(4f). \]  

(4)

Thinner deposits can be detected, but their thickness cannot be determined, and the reflection amplitudes will be decreased by destructive interference (Widess, 1973).

While it can be shown from these equations that many sulfide deposits meet or exceed the size requirements for both detection and imaging (for example, a 500 m diameter × 15 m thick deposit could easily be imaged at a depth of 2 km, assuming a peak frequency of 100 Hz and a formation velocity of 6.0 km/s), early tests in mining camps were inconclusive (e.g., Dahle et al., 1985; Reed, L., 1993, Mineral Industry Technology Council of Canada report), in part because the acoustic properties of the sulfide minerals themselves were poorly understood, but also because significant differences in target size, structure, and acoustics between hard and soft rock environments had not been fully taken into account. In particular, the signal-to-noise (S/N) ratio is anomalously low in hard rock terrains, the targets are typically point sources or scatterers rather than continuous reflectors, and they are often steeply dipping (Eaton, 1999).

To assess and solve these problems, the Geological Survey of Canada (GSC) recently embarked on a major collaborative research program with INCO, Falconbridge, and Noranda involving integrated laboratory, logging, modeling, and seismic tests at six mining camps in Canada, including Sudbury, Kidd Creek, and Manitouwadge in Ontario, Matagami and Selbaie in Quebec, and Bathurst in New Brunswick. The objectives of the laboratory studies were first to determine the basic acoustic properties of the major sulfide minerals from measurements of their compressional wave velocities (\( V_p \)) and densities at elevated pressures, and then to determine for each camp the pairs of lithologies which might be expected to produce strong reflections. Following the laboratory studies, velocity and density logs were then run in selected boreholes in each camp to determine if the laboratory results persisted at formation scales. If the results of these tests were promising, seismic modeling based on the laboratory and logging results plus the known geology in each camp was performed to guide the subsequent acquisition and interpretation of seismic reflection data. Vertical seismic profiling (VSP) and/or 2-D and 3-D multichannel seismic (MCS) surveys were then conducted over known ore deposits and marker horizons in each camp using state-of-the-art technology to map the geology at depth and determine if the deposits themselves could actually be detected and imaged. While the surveys were based on oil-field techniques, many changes were made to accommodate the unusual conditions encountered in hard rock terrains. For example, dynamite was used as the source because of its high-frequency content, and particular care was taken to ensure high-fold coverage and good shot and receiver coupling to bedrock to compensate for low S/N ratios. In addition, large shot-receiver offsets or VSP techniques were used where the targets were steeply dipping. Finally, since the targets were small, unconventional processing sequences based on Born scattering were often used to process the data (Eaton et al., 1997; Milkereit et al., 1997).

The results of these studies have been spectacular. The laboratory studies have provided a quantitative basis for predicting the reflectivity of an ore body of any composition in any setting (Salisbury et al., 1996), while the seismic studies successfully detected all of the known deposits and identified several new targets to be tested by drilling. Preliminary seismic results have already been published for several of these studies (Milkereit et al., 1992, 1996; Eaton et al., 1996) and the results of many of the more recent surveys conducted during this program, including 2- and 3-D surveys in Bathurst, Manitouwadge, Matagami, and Sudbury, were presented at Exploration ’97 (Adam et al., 1997; Eaton et al., 1997; Milkereit et al., 1997; Roberts et al., 1997; Salisbury et al., 1997). The purpose of the present paper is to outline the basic acoustic properties of sulfides and to show, through a case study involving laboratory, logging, and seismic imaging tests at the Halfmile Lake deposit in the Bathurst camp, how these properties govern the reflectivity of massive sulfides.

**ACOUSTIC PROPERTIES OF SULFIDES**

While the acoustic properties of silicate rocks are well known from decades of laboratory studies (e.g., Birch, 1960; Christensen, 1982), until very recently the properties of sulfides were so poorly known that it was difficult to predict whether or not they should be reflectors. The principal difficulty was that while the velocities and densities of some sulfide minerals, such as pyrite (py) and sphalerite (sph) were well known (Simmons and Wang, 1971), the properties of other volumetrically and thus acoustically important minerals such as chalcopyrite (cpy) and pyrrhotite (po) had never been measured, making it difficult to estimate the properties of mixed sulfide deposits.

To answer this question, we measured the densities and compressional wave velocities of a large suite of ore and host rock samples of known composition in the laboratory at confining
pressures ranging from 0 to 600 MPa using the pulse transmission technique of Birch (1960). In addition to ores of mixed composition, samples of pure py, sph, po, and cpy were measured to establish the theoretical limits of the velocity-density field for common ores. The results, summarized in Figure 1 from Salisbury et al. (1996) for data at a standard confining pressure of 200 MPa (the crack closure pressure), show several important trends:

1) As predicted from earlier studies, the velocities of the host rocks increase with density along the Nafe-Drake curve for silicate rocks (Ludwig et al., 1971).

2) The sulfides, however, lie far to the right of the Nafe-Drake curve in a large velocity-density field controlled by the properties of pyrite, which is fast and dense (8.0 km/s, 5.0 g/cm³), pyrrhotite, which is very slow and dense (4.7 km/s, 4.6 g/cm³), and sphalerite and chalcopyrite which have intermediate and very similar velocities and densities (∼5.5 km/s, 4.1 g/cm³).

3) The properties of mixed and disseminated sulfides lie along simple mixing lines connecting the properties of end-member sulfides and felsic or mafic gangue. Thus, for example, velocities increase dramatically with increasing pyrite content, but they actually decrease with increasing sphalerite, chalcopyrite, or pyrrhotite content along trends which can be calculated using the time-average relationship of Wyllie et al. (1958).

4) If lines of constant acoustic impedance (Z) corresponding to the average impedances of mafic and felsic rocks are superimposed on the sulfide fields as in Figure 1, it is clear that most sulfide ores have higher impedances than their felsic or mafic hosts. Since a reflection coefficient of 0.06 is sufficient to give a strong reflection, then in principle, massive sulfides with the appropriate geometry should be strong reflectors in many common geologic settings. For example, massive pyrrhotite should be readily detectable in felsic settings, and any combination of sphalerite, chalcopyrite, and pyrite should be a strong to brilliant reflector in most mafic and felsic settings, depending on the pyrite content.

CASE STUDY: SEISMIC REFLECTIONS FROM THE HALFMILE LAKE DEPOSIT, BATHURST

While the laboratory results presented above show that massive sulfides should often be strong reflectors, it is also clear that the reflectivity of any given deposit will be strongly influenced by local conditions, such as the size and configuration of the deposit, its actual mineralogy, and the composition and metamorphic grade of the country rock. Thus to evaluate the method, it was necessary to study the actual seismic response of several deposits at different scales of investigation.

The Bathurst mining camp in New Brunswick was selected for one of these studies because it provides an excellent opportunity to examine the seismic response of volcanogenic massive sulfide deposits in low-grade metamorphic settings. The results, which were obtained over the Halfmile Lake deposit, the largest undeveloped deposit in the camp, provide a particularly clear example, not only of reflections from a massive sulfide deposit, but of the factors which must be taken into account in imaging these bodies.

Geology of the Halfmile Lake deposit

The Halfmile Lake deposit is an extensive massive sulfide sheet which ranges from 1 to 45 m in thickness and contains 26 million tons of total sulfides. Mineralization is characterized by py-po-rich layered sulfides and po-rich breccia-matrix sulfides with variable amounts of sphalerite, galena, and arsenopyrite. The deposit is hosted by a thick sequence of turbidites, felsic volcanic and epiclastic rocks, argillites, and intermediate volcanic rocks of Cambro-Ordovician age (Adair, 1992). Four periods of fold deformation are documented in the deposit area and are accompanied by faulting. The deposit occurs on the overturned south limb of a large antiform (Figure 2). The sulfide sheet extends 3 km along strike (Figure 2) and has been drilled to a depth of 1.2 km. It is structurally overlain (stratigraphic footwall) by a stringer zone containing between 5 and 30% stringer po and cpy (Figure 3). The overall dip of the stratigraphy is 45° to the north-northwest, but structural influences locally steepen dips to near vertical. Metamorphism is greenschist facies, and the sheet displays 100 m of topography.

Hosted within the sulfide sheet are two significant build-ups of massive sulfides in the Upper and Lower Zones (Figure 3), where the thickness of the sulfides ranges between 5 and 45 m. The most important and largest undeveloped deposit in the camp is the Lower Zone, which contains 6.1 million tons of 9.7% Zn, 3.34% Pb, 0.1% Cu, and 43 g/ton Ag. The Halfmile Lake deposit and specifically the Lower Zone were selected for this study because it had been carefully mapped and delineated by drilling, core was available for laboratory studies, drillholes were still open for logging and VSP tests, the size and dip of the deposit seemed appropriate for detection.
using 2-D surface seismic techniques and, since it had never been mined, there would be no spurious reflections from mine workings.

**Laboratory impedance measurements**

To determine which lithologies were potential reflectors at Halfmile Lake, velocities and densities were measured in the laboratory at elevated pressures on minicores cut from 28 surface and drill core samples representing all of the major ore and host rock lithologies along the seismic line. Since sedimentary and metamorphic rocks are often anisotropic, velocities were measured parallel and perpendicular to bedding, banding, or foliation in many samples, bringing the total number of measurements to 53. The results, presented at a confining pressure of 200 MPa in Figure 4, show that the host rocks all have very similar average velocities and densities (about 6.0 km/s and 2.75 g/cm³). This initially surprising result is due to the fact that the felsic igneous rocks (rhyolite, quartz porphyry, tuff) and the metasediments all have very similar compositions, while the mafic rocks are actually basaltic andesites of intermediate composition in which the velocities have been depressed by the alteration of mafic minerals to chlorite by greenschist facies metamorphism. The Halfmile Lake ores, on the other hand, display a wide range of velocities (5.1–7.3 km/s) due to varying proportions of po and py. Interestingly, the iron formation sample plots in the velocity-density field for the sulfides due to the high intrinsic velocity and density of magnetite (7.4 km/s, 5.2 g/cm³). As a consequence, the impedance contrasts between the various country rock lithologies at Halfmile Lake should be small, while the contrast between any of the ores and the country rock will be very large. Since an impedance contrast of 2.5 is sufficient to give a strong reflection, this implies that at least in terms of their acoustic properties, the ores at Halfmile Lake should be strong reflectors in a virtually transparent host rock setting.

**Geophysical logging**

Once the laboratory measurements had been completed, two boreholes through the deposit (holes HN 94-63 and HN 94-65 in Figure 3) were logged by the GSC Mineral Resources Division using slim-hole sonic velocity and density tools to determine if the impedance differences measured in the laboratory persist at formation scales. The results, presented in Figure 5 for the deeper of the two holes, show that the densities range narrowly from 2.6 to 2.75 g/cm³ throughout the silicate rocks, but increase erratically to values as high as 2.95 g/cm³ in the massive sulfides, while negative excursions correspond to faults.

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**LEGEND**

- Sediments
- Qtz Porphyry
- Rhyolite, Tuff
- Basaltic andesite
- Gabbro
- Sulphides

**Fig. 2.** Geologic map of Halfmile Lake deposit showing location of 2-D seismic line presented in Figure 7. Geologic cross-section shown in Figure 3 extends from station 1 to station 166 (10–1660 m along line). Geophysical logging was conducted in holes HN 94-63 (Figure 5) and HN 94-65. Offset VSP shown in Figure 6 was conducted in hole HN 92-30. Dashed arrow shows axis and plunge of F1 antiform. Inset shows regional setting of Halfmile Lake deposit.
marked by thin intervals of fault gouge or breccia. Similarly, the velocity log varies from 5.5 to 6.0 km/s throughout most of the hole, with negative spikes corresponding again to narrow faults. Significantly, the velocity-density product, or impedance log, shows very little variation about a mean of about 15, except for the ores, which reach values of about 20, and the faults, which reach values as low as 11. While the absolute values of the velocity and impedance logs are lower than the laboratory results due to differences in pressure, the impedance contrasts are similar to those predicted from laboratory studies, implying that the massive sulfides will be strong reflectors, while the country rock will be transparent except possibly where cut by faults.

**Vertical seismic profiling**

While the laboratory and logging results were promising, they were not definitive because they were obtained at much higher frequencies than seismic surveys (1 MHz and 50 KHz versus 10–200 Hz) and the propagation paths were much shorter (2–5 cm and 1–2 m versus a few kilometers). VSP provides a more convincing test because the method can be used to determine if reflections are actually generated at seismic frequencies and if they are sufficiently strong to be detected over propagation paths of 1 km or more. To this end, an offset VSP survey was conducted in borehole HN 92-30 by the University of Alberta using 350 g Pentolite charges in a series of shallow

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**FIG. 3.** Simplified geologic cross-section through Halfmile Lake deposit based on drilling results projected onto seismic line between stations 1 and 166. UZ = Upper Zone, LZ = Lower Zone. VSP survey (Figure 6) was conducted in hole HN 92-30 (shots at X) and logging was conducted in holes 94-63 and 94-65. No vertical exaggeration.

**FIG. 4.** Average compressional wave velocity \( (V_p) \) at 200 MPa versus density for ore and host rock samples from the Halfmile Lake deposit superimposed on velocity-density fields for sulfides and silicate rocks shown in Figure 1. Also shown are lines of constant acoustic impedance for mafic rocks \( (Z = 20) \) and felsic rocks \( (Z = 17.5) \). Impedances of Halfmile Lake ores (ellipse) are much greater than those of their silicate hosts.
(3–6 m) holes drilled to the top of basement about 100 m north of hole HN 92-30 (X in Figure 3) and a 3-component borehole seismometer clamped at 5 m intervals as the tool was raised from a depth of 575 m to the surface.

Analysis of first arrival traveltimes shows that the crust has an average $P$-wave velocity (5.55 km/s) consistent with the logging data, while the reflection results, presented in Figure 6 after routine processing (upgoing wavefield separation, high-pass 50–290 Hz filter, deconvolution, scaling, first break mute) and transformation to geometric coordinates using the CDP transform method (Wyatt and Wyatt, 1984; Hardage, 1985; Kohler and Koenig, 1986), show a prominent, north-dipping reflector between 300 and 400 m depth which corresponds to the massive sulfide deposit south of the borehole (Figure 3). Interestingly, a deeper sulfide horizon was also imaged at the base of the hole. As predicted from the laboratory and logging studies, no other contacts in the immediate vicinity have sufficiently large impedance contrasts to produce reflections, and the faults are too thin to detect. From the results of this test, it is thus clear that the Halfmile Lake deposit generates strong reflections at seismic frequencies, these reflections propagate for significant distances in basement, and the deposit can be readily imaged using borehole VSP techniques and conventional sources.

**Multichannel seismic profiling**

While obviously successful, the borehole VSP survey conducted at Halfmile Lake did not prove that 2-, or 3-D surveys conducted at the surface would be successful. Despite the many similarities between the two techniques, significant differences still remain: The source to receiver paths are shorter for VSP surveys, the S/N ratio is improved by clamping the receiver in basement rather than placing it at the surface, and the overburden path is eliminated.

The definitive test of the seismic reflection method is thus to conduct a 2-, or 3-D survey over the deposit from the surface as if no boreholes were available. To this end, a 2-D multichannel survey was conducted over the deposit along a 5.85 km line which intersects the deposit at its southern end and extends down-dip for a considerable distance to the north (Figure 2), with downhole control provided by the VSP and logging results. The survey was conducted by Enertec Geophysical Services under contract to Noranda using 340 g Pentolite charges in holes drilled to basement every 40 m along the line; a portable, state-of-the-art, 480-channel, 24-bit recording system; and 14 Hz receivers laid out along three parallel lines spaced 50 m apart: a center line with groups every 10 m, 9 phones/station, giving 30 fold coverage, and a line to either side with a 20 m group spacing, 9 phones/station, giving 15 fold coverage.

Although shooting conditions were difficult and the field records were very noisy, careful processing involving static corrections, scaling, the application of a high-pass filter, deconvolution, common-midpoint binning, stacking velocity analysis, noise suppression, and poststack scaling gave a clear image of the ore body (Figure 7) which coincides with the known location of the deposit after migration. As in the VSP survey,
the country rock was weakly reflective to virtually transparent along the rest of the line. The results at Halfmile Lake thus demonstrate not only that massive sulfides can be detected using surface seismic reflection techniques but that nothing else in the immediate vicinity of the line causes strong reflections. Thus at Halfmile Lake, seismic reflection provided relatively little new information about deep structure, but the method appears to be almost ideal for exploration.

CONCLUSIONS

From the results of this study, it is clear that massive sulfides can make strong reflections in hard rock settings and that they can be detected using state-of-the-art seismic reflection techniques. This has major implications, both for exploration in the Bathurst camp itself and for the mining industry as a whole.

Since the first major discovery in Bathurst more than 40 years ago, more than 100 base metal deposits, 35 with defined tonnage, have been identified in the upper few hundred meters of basement in the camp using surface mapping and potential field techniques. As in many camps, however, the known shallow reserves are declining at Bathurst, forcing exploration to deeper levels. Statistically, there should be just as many deposits per unit volume at greater depths in the camp, but these have proven difficult to find because the surface geology is too complex to project to depth and potential field methods lose their resolution at depths greater than a few hundred meters. Seismic reflection, however, appears to be an ideal tool for deep exploration at Bathurst and elsewhere because it has high resolution to the full depth limits of mining (∼3 km) and because it can scan large volumes of crust at a cost which is low compared to deep wildcat or delineation drilling (Pretorius et al., 1997). While conditions at Bathurst appear to be particularly suitable for seismic exploration, recent experimental surveys over deposits in quite different settings such as Matagami, Kidd Creek, and Sudbury (Adam et al., 1997; Eaton et al., 1997; Milkereit et al., 1997) are equally encouraging, suggesting that high-resolution seismic reflection techniques can be modified.
to meet the deep exploration needs of the mining industry in the new millennium.

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