Physical Properties and Seismic Imaging of Massive Sulphides

Salisbury, M.H.[1], Milkereit, B.[2], Ascough, G.L.[3], Adair, R.[3], Schmitt, D.[4], and Matthews, L.[5]

1. Geological Survey of Canada, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada
2. Institut fur Geophysik, Universitat zu Kiel, Kiel, Germany
3. Noranda Mining and Exploration, Inc., Bathurst, New Brunswick, Canada
4. Department of Geology, University of Alberta, Edmonton, Alberta, Canada
5. Noranda Mining and Exploration, Inc., Calgary, Alberta, Canada

ABSTRACT

Laboratory studies conducted by the Geological Survey of Canada (GSC) show that the acoustic impedances of massive sulphides can be predicted from the physical properties (Vp, density) and modal abundances of common sulphide minerals using simple mixing relations. Most sulphides 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, the GSC has conducted a series of 1-, 2- and 3-D seismic experiments with industry to image known ore bodies in central and eastern Canada. In one of the most recent tests, conducted at the Halfmile Lake Cu-Zn deposit in the Noranda 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 dramatically confirmed by the detection of strong reflections from the deposit using vertical seismic profiling (VSP) and 2-D multi-channel seismic (MCS) imaging techniques.

INTRODUCTION

At the turn of the last century, 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 over 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 principle 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 Cu and Zn 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 sulphides.

In principle, a sulphide deposit can be imaged using seismic reflection techniques if three 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 *Zo* and *Zc* 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,

$$R = \frac{Z_o - Z_c}{Z_o + Z_c} \qquad [1]$$

In practice, an impedance difference of 2.5 x 10^5 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 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,

$$d_F = \sqrt{2z\frac{v}{f}} \qquad [2]$$

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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, $d_{\min}$, which can be detected in practice is

$$d_{min} = \frac{v}{f} \quad [3]$$

3. For the upper and lower contacts of the body to be resolved, the deposit must be at least ¼ wavelength thick, or,

$$t_{min} = \frac{v}{4f} \quad [4]$$

where t_{min} is the minimum thickness of the deposit.

As before, 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 sulphide 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, 1993), in part because the acoustic properties of the sulphide 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.

To assess and solve these problems, the GSC recently embarked on a major collaborative research program with INCO, Falconbridge and Noranda involving integrated laboratory, logging, modelling and seismic tests at six mining camps in Canada, including Sudbury, Kidd Creek and Manitouwadge in Ontario, Matagami and Selbaie in Québec and Bathurst in New Brunswick. The objectives of the laboratory studies were first to determine the basic acoustic properties of the major sulphide minerals from measurements of their compressional wave velocities (V_p) and densities (ρ) 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 modelling 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 multi-channel 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 sound source 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.*, Milkereit *et al.*, this volume).

The results of theses 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 which are now being 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, are being presented at this conference for the first time (Roberts *et al.,* Adam *et al.*, Milkereit *et al.,* Eaton and Milkereit, this volume). The purpose of the present paper is to outline the basic acoustic properties of sulphides 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 sulphide deposits.

ACOUSTIC PROPERTIES OF SULPHIDES

While the acoustic properties of silicate rocks are well known from decades of laboratory studies (e.g., Birch, 1960; Christensen, 1985), until very recently, the properties of sulphides were so poorly known that it was difficult to predict whether or not they should be reflectors. The principle difficulty was that while the velocities and densities of some sulphide 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 aggregate properties of mixed sulphide 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 sulphides, 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/cm^3), pyrrhotite, which is very slow and dense (4.7 km/s, 4.6 g/cm^3) and sphalerite

and chalcopyrite which have intermediate and very similar velocities and densities (~5.5 km/s, 4.1 g/cm^3).

3. The properties of mixed and disseminated sulphides lie along simple mixing lines connecting the properties of end-member sulphides 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 that 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 sulphide fields as in Figure 1, it is clear that most sulphide 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 sulphides 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.

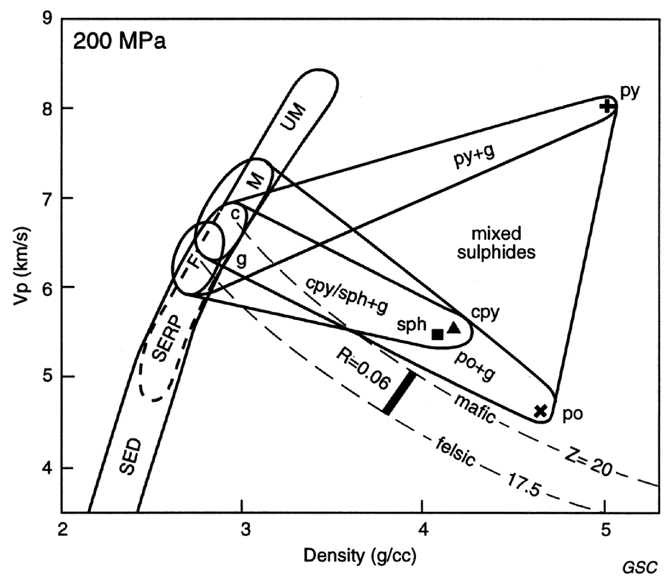

Figure 1: *Velocity (Vp)-density fields for common sulphide ores and silicate host rocks at 200 MPa. Ores: py, pyrite; cpy, chalcopyrite; sph, sphalerite; po, pyrrhotite. Silicate rocks along Nafe-Drake curve: SED, sediments; SERP, serpentinite; F, felsic; M, mafic; UM, ultramafic; g, gangue. c = carbonate. Dashed lines represent lines of constant acoustic impedance (Z) for felsic and mafic rocks. Bar shows minimum impedance contrast required to give a strong reflection (R=0.06).*

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

While the laboratory results presented above show that massive sulphides 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 study because it provides an excellent opportunity to examine the seismic response of VMS 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 sulphide 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 sulphide sheet containing 26 MT of total sulphides. Mineralization is characterized by py-po-rich layered sulphides and po-rich breccia-matrix sulphides with variable amounts of sphalerite, galena and arsenopyrite with a thickness of between 1 and 45 m. 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 sulphide 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 NNW, but structural influences locally steepen dips to near vertical. Metamorphism is greenschist facies and the sheet displays 100 m of topography.

Hosted within the sulphide sheet are two significant buildups of massive sulphides in the Upper and Lower Zones (Figure 3) where the thickness of the sulphides ranges between 5 and 45 m. The most important, and largest undeveloped deposit in the camp is the Lower Zone which contains 6.1 MT of 9.7% Zn, 3.34% Pb, 0.1% Cu and 43 g/t 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

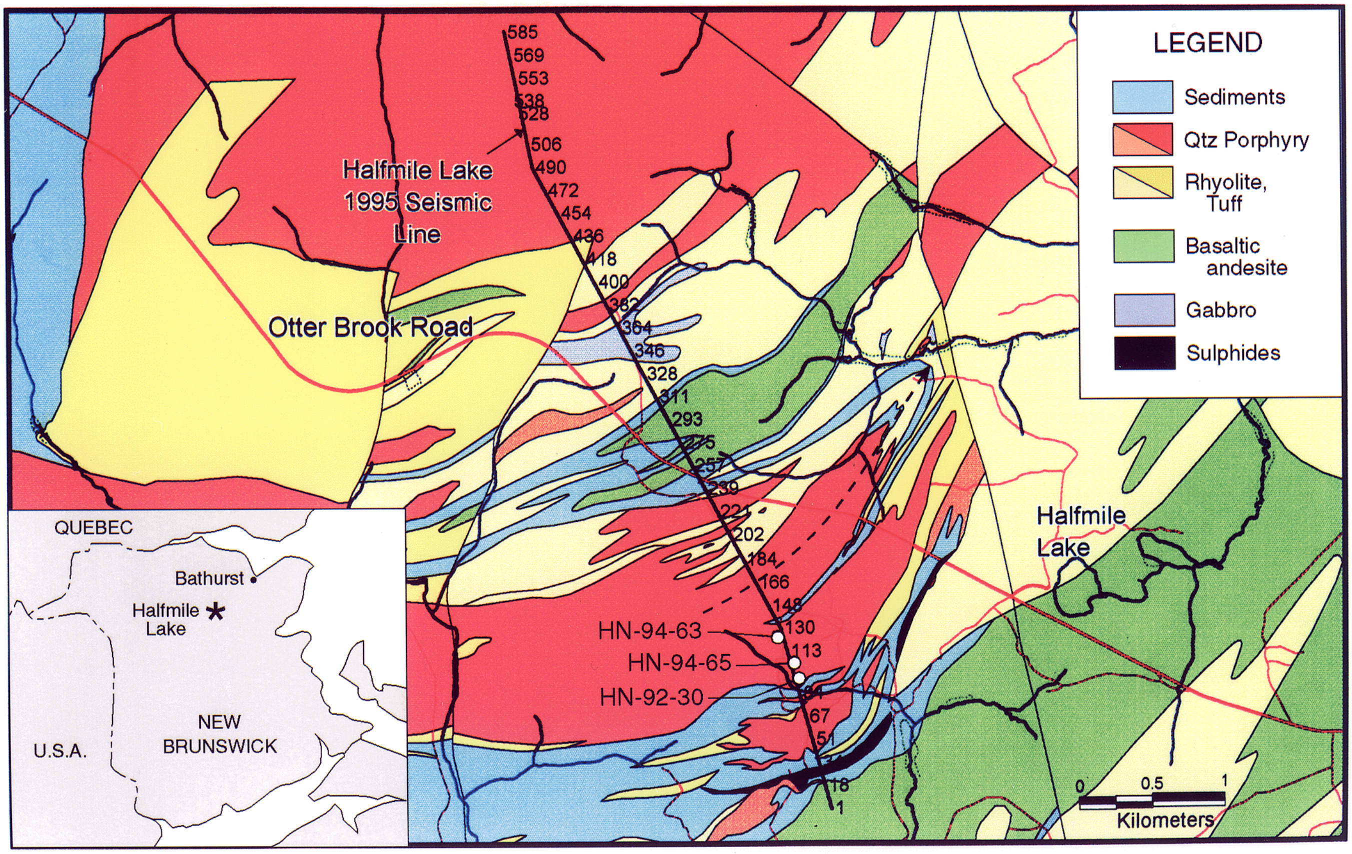

Figure 2: *Geology map of Halfmile Lake deposit showing location of 2-D seismic line presented in Figure 7. Geologic cross-section shown in Figure 3 extends from stations 1–166 (10–1660 m along line). Geophysical logging was conducted in holes HN 94-63 (Figure 5) and HN 94-65. Offset VSP shown in Figure 6 was conducted in hole HN 92-30. Inset shows regional setting of Halfmile Lake deposit. Dashed arrow shows axis and plunge of F1 antiform.*

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 sulphides due to the high intrinsic velocity and density of magnetite (7.4 km/s, 5.2 g/cm^3). 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's Mineral Resources Division using slimhole 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 2.6–2.75 g/cm^3 throughout the silicate rocks, but increase erratically to values as high as 2.95 g/cm^{3}in the stringer zone, then dramatically to about 3.4 g/cm^3 in the massive sulphides, while negative excursions correspond to faults marked by thin intervals of fault gouge or breccia. Similarly, the velocity log varies from 5.5–6.0 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

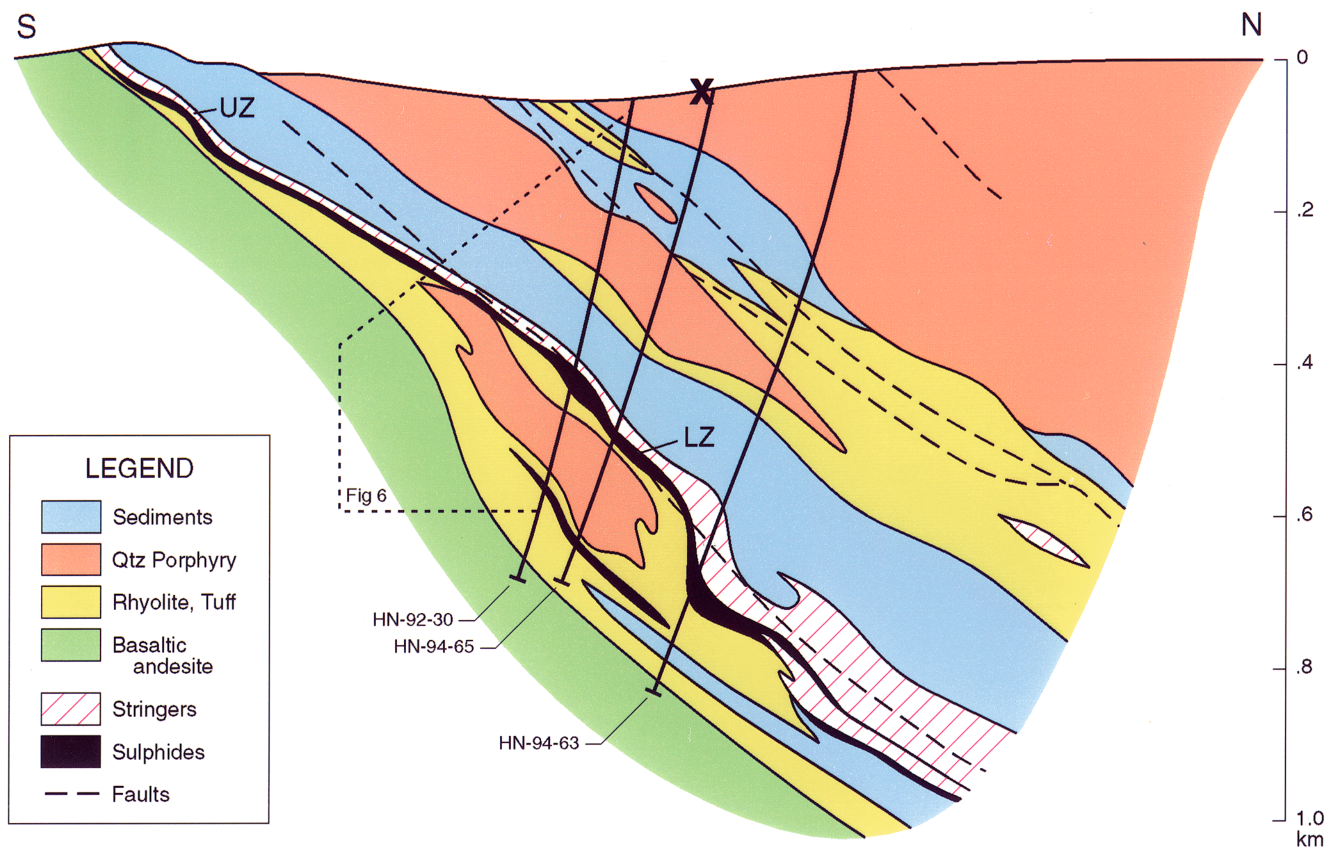

Figure 3: *Simplified geologic cross-section through Halfmile Lake deposit based on drilling results projected onto seismic line between stations 1–166. UZ: Upper Zone; LZ: Lower Zone. VSP survey (Figure 6) was conducted in hole HN 92-30 (shots at X) and logging was conducted in holes 94-63 and 94-65.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

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 sulphides 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 kilometres). Vertical seismic profiling (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 (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 three-component borehole seismometer clamped at 5 m intervals from a depth of 575 m to the surface.

Analysis of first arrival travel times 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 sulphide deposit south of the borehole (Figure 3). Interestingly, a deeper sulphide 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

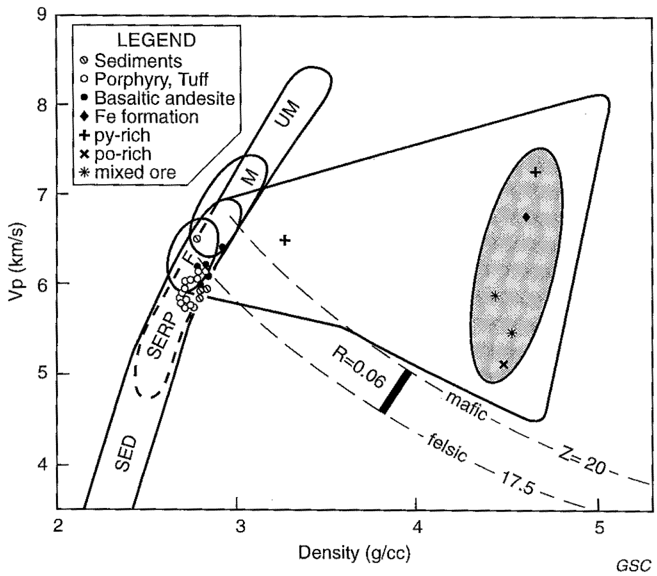

Figure 4: *Average compressional wave velocity (Vp) at 200 MPa versus density for ore and host rock samples from the Halfmile Lake deposit superimposed on velocity-density fields for sulphides and silicate rocks shown in Figure 1. Also shown are lines of constant acoustic impedance for mafic rocks (Z = 20) and felsic rocks (17.5). Impedances of Halfmile Lake ores (ellipse) are much greater than those of their silicate hosts.*

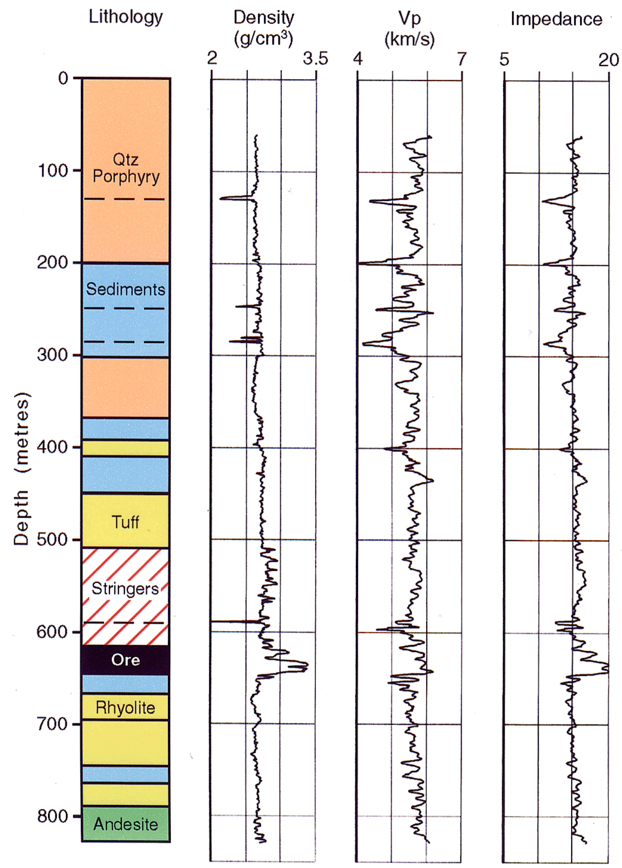

Figure 5: *Density, velocity (Vp) and calculated impedance versus depth in hole HN 94-63 from geophysical logging. Fault gouge in core indicated by dashed lines. Note high impedance of massive sulphides.*

reflections at seismic frequencies, that these reflections propagate for significant distances in basement and that the deposit can be readily imaged using borehole VSP techniques and conventional sources.

Multi-channel 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 multi-channel survey was conducted over the deposit along a 5.85 km long line which intersects the deposit at its southern end and extends downdip for a considerable distance to the north (Figure 2), with 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, CMP binning, stacking velocity analysis, noise suppression and post-stack 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 sulphides can be detected using surface seismic reflection techniques but that nothing else in the immediate vicinity 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.

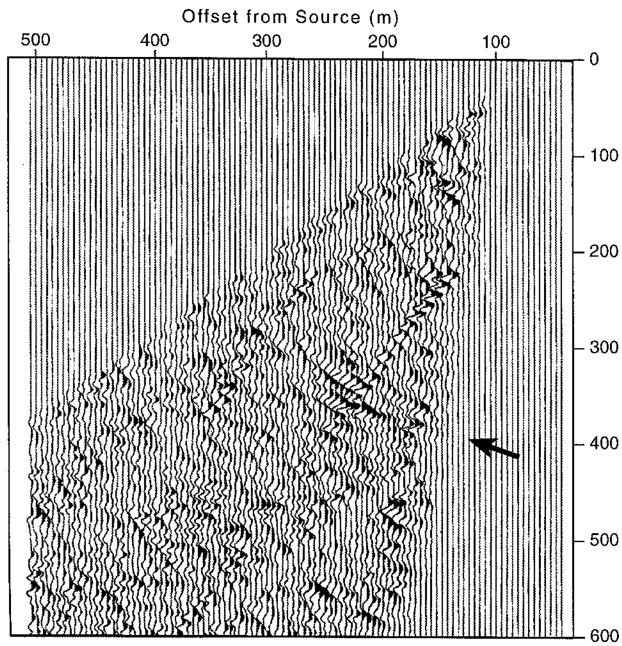

Figure 6: *CDP transform of VSP survey in borehole HN 92-30 showing reflection from Halfmile Lake deposit (arrow). X indicates location of shots. Reflections are also observed from a thin sulphide layer between 550–600 m (see Figure 3).*

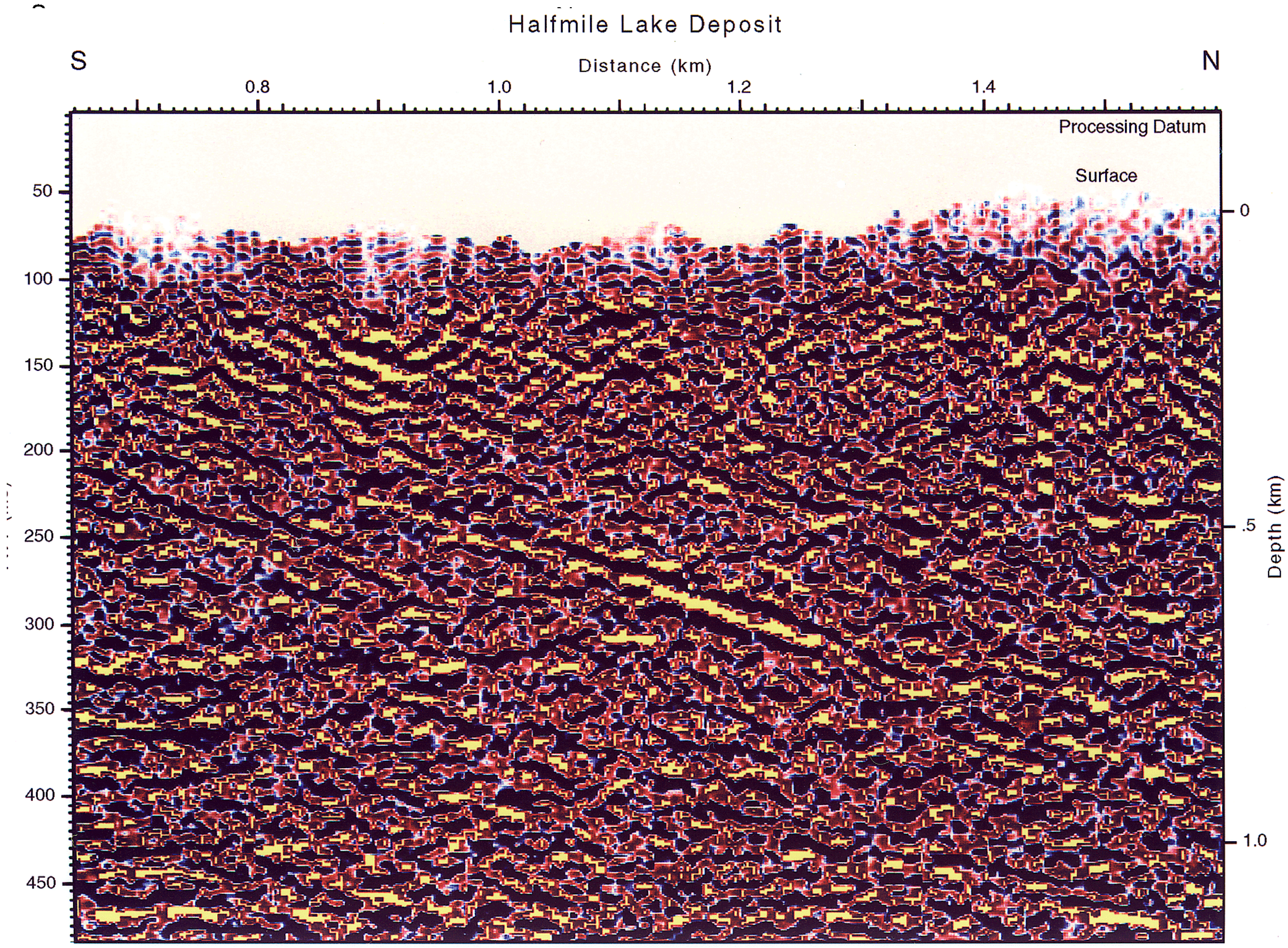

Figure 7: *Unmigrated 2-D multi-channel seismic image of the Halfmile Lake deposit. TWT, two-way travel time.*

CONCLUSIONS

From the results of this study, it is clear that massive sulphides 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, for both exploration in the Bathurst camp itself and the mining industry as a whole.

Since the first major discovery in Bathurst over 40 years ago, more than 100 base metal deposits, 35 with defined tonnage, have been identified in the upper few hundred metres 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 metres. 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 that is low compared to deep wildcat or delineation drilling (Pretorius and Trewick, this volume). 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.*, Eaton and Milkereit, Milkereit *et al.*, this volume) 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 coming millenium.

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