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Seismic Imaging of Massive Sulfide Deposits: Part II. Reflection Seismic Profiling*

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Abstract

Seismic reflection profiling, the dominant geophysical method for hydrocarbon exploration, has the potential to provide images of regional structure for mineral exploration in the crystalline crust and direct detection of large, massive sulfide orebodies. Previous tests of traditional seismic methods in hard-rock environments have had mixed success. Based on these earlier results, we have tailored acquisition and processing strategies to conditions in the Canadian Shield. We illustrate these methods using an example from the Sudbury basin, a rich mineral-producing region. Because of structural complexity that complicates interpretation of the seismic images, the seismic data are integrated with detailed three-dimensional forward modeling based on physical properties studies, mine geology, and well logging. Through this integrated approach, we show that massive sulfides can produce a characteristic seismic reflection response, and that surface seismic reflection profiling may be used to detect and delineate deep, large massive sulfide deposits accurately in a complex geologic setting characterized by moderate dips.

Introduction

CONVENTIONAL surface geophysical techniques for mineral exploration are capable of penetrating to depths of 100 to 300 m in crystalline crust, yet ore can be mined from depths exceeding 2,000 m. Reliable geophysical information about greater depths would result in an improved geologic interpretation of crustal structure and more accurate assessment of mineral potential. Over the past several years, high-frequency reflection seismic surveys have been conducted by Lithoprobe and industrial partners in the Matagami (Milkereit et al., 1992a), Selbaie (Milkereit et al., 1992c), and Noranda (Verpaelst et al., 1995) camps in Quebec, the Buchans camp in Newfoundland (Spencer et al., 1993), the Thompson camp in Manitoba (White et al., unpub. data), and the Sudbury camp in Ontario (Milkereit et al., 1992b). From these reconnaissance studies two new applications of seismic reflection profiling for mineral exploration have emerged: terrain analysis, which provides a regional framework and geologic insight not possible from other geophysical techniques (see review by Clowes, 1994), and direct detection of an orebody through which massive sulfide bodies are delineated by characterization of their seismic scattering response (this paper). Although results from two-dimensional reconnaissance seismic profiles acquired across key geologic targets provide important information on gross structure and regional geologic setting, there have been problems integrating this new mapping technique into normal exploration procedures. Until recently, comprehensive seismic velocity studies of massive sulfide ores did not exist. Sparse and conflicting reports about the velocities of ores (Goulty, 1993) did not provide a sound justification for using relatively expensive seismic mapping techniques. In addition, borehole geophysical logs such as γ-γ density and sonic velocity, important for the interpretation and calibration of reflection seismic data, have not been routinely run in slim diamond drill holes. This lack of "ground truthing" stimulated an ongoing controversy in the geosciences regarding the causes of seismic reflections in the crystalline crust.

To date, there has been no reported successful seismic feasibility study to detect massive sulfides directly in crystalline rocks (Reed, 1993, and references therein). For this reason, reflection seismic profiling for mineral exploration was considered unproven technology, and the high costs of acquiring high-quality seismic data provided little incentive for this new mapping approach. Recently, Milkereit et al. (1994b) demonstrated the use of integrated seismic and slim hole geophysical studies in the crystalline crust. Salisbury et al. (1996) show that massive sulfide ores are characterized by high acoustic impedances (Z), the product of compressional wave velocity (v_P) and density (ρ). Their physical rock property study concluded that massive sulfide bodies should make strong seismic reflectors in many common geologic settings. In this paper we present results from a high-frequency seismic profile across a deep seated mineral deposit beneath the South Range of the Sudbury structure which confirm this conclusion.

Sudbury Seismic Surveys

The origin of the Sudbury structure (Fig. 1) and associated ore deposits has long been a subject of debate (Pye et al., 1984). Understanding the shape of the Sudbury structure at depth is important, as it is relevant to the long-term exploration of its vast mineral deposits. Since 1990, integrated geophysical studies have been conducted across the Sudbury structure, as part of the Canadian Lithoprobe project (Boerner et al., 1994). Results of a reconnaissance seismic survey, conducted along transect A-A′ (Fig. 1), presented the first picture of the highly asymmetric deep geometry of the

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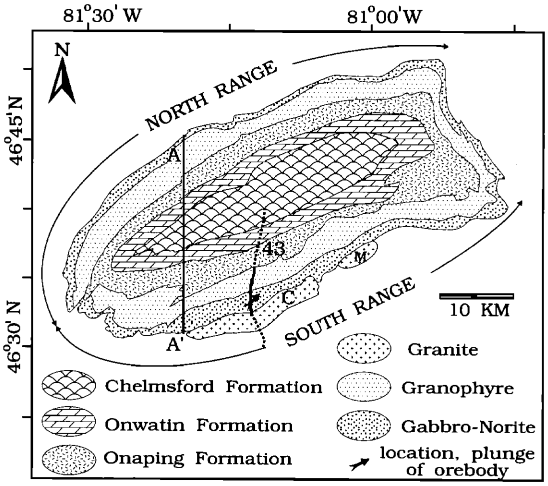

FIG. 1. Map showing geology of the Sudbury structure and location of Lithoprobe seismic lines discussed in this study. Seismic sections shown in Figures 3, 4, and 5 are taken from the solid portion of line 43. C = Creighton Granite, M = Murray Granite.

Sudbury structure (Fig. 2a; Milkereit et al., 1992b; Wu et al., 1995), thus demonstrating the potential for using high-frequency seismic reflection profiling as a regional exploration tool. An example of the high-frequency reflection data from the northern part of the Sudbury structure is shown in Figure 2b. Prominent reflections or changes in reflection character occur at the Onaping-granophyre contact (A), the granophyre-norite transition (B), and the norite-footwall contact. Figure 2 demonstrates that surface seismic data allow the thickness, depth, and lateral continuity of the important norite layer to be determined. The early success of these studies led to further development, testing, and calibration of new seismic exploration technology for the crystalline crust.

In 1993, another high-resolution seismic reflection profile (line 43, Fig. 1) was acquired across the South Range of the Sudbury structure. The profile cut across a large, thick pyrrhotite body which lies approximately 900 to 1,500 m below the surface along the norite-footwall contact in the South Range. This contact dips moderately (45°–60°) to the north. In the study area (Fig. 1), the rocks are relatively undeformed and good geologic control is provided by deep boreholes. The seismic source consisted of two Vibroseis trucks sweeping four times at every station. The profile extended 20 km north across the Sudbury Igneous Complex from the Creighton granite in the footwall, to the Onwatin Formation shale in the center of the structural basin. All seismic data were collected using a 240-channel telemetry acquisition system with in-field stacking, noise rejection, and correlation capabilities (Milkereit et al., 1994a), and with source and receiver spacing of 20 m to give a nominal stacking fold of 120. Symmetric split-spread acquisition geometry resulted in maximum offsets of 2,400 m. Geophones with a resonant frequency of 30 Hz were used to attenuate ambient low-frequency noise. Further improvement of the signal/noise ratio during data acquisition was achieved by extending both band width and sweep length (12 s linear upsweep from 30 to 140 Hz) and utilizing diversity stacking to suppress random noise bursts, traffic, etc. A typical field record (Fig. 3) shows weak energy from a dipping reflector (R). Strong refracted compressional (P) and shear (S) waves as well as source-generated air waves (A) interfere with reflections and must be attenuated during data processing.

The data processing sequence had to take into account highly variable overburden conditions and steeply dipping geologic structures. Various data processing options were evaluated and a robust processing sequence was developed, which consists of computation of weathering static corrections, deconvolution, time variant band-pass filtering, crooked line binning, dip moveout (DMO) processing, detailed stacking velocity analysis, and migration (Wu et al., 1995). Here, as elsewhere in the Canadian Shield, highly variable overburden thicknesses and lateral velocity variation in glacial drift posed major challenges for processing high-frequency seismic data. Typically, low velocities of less than 600 m/s are observed for

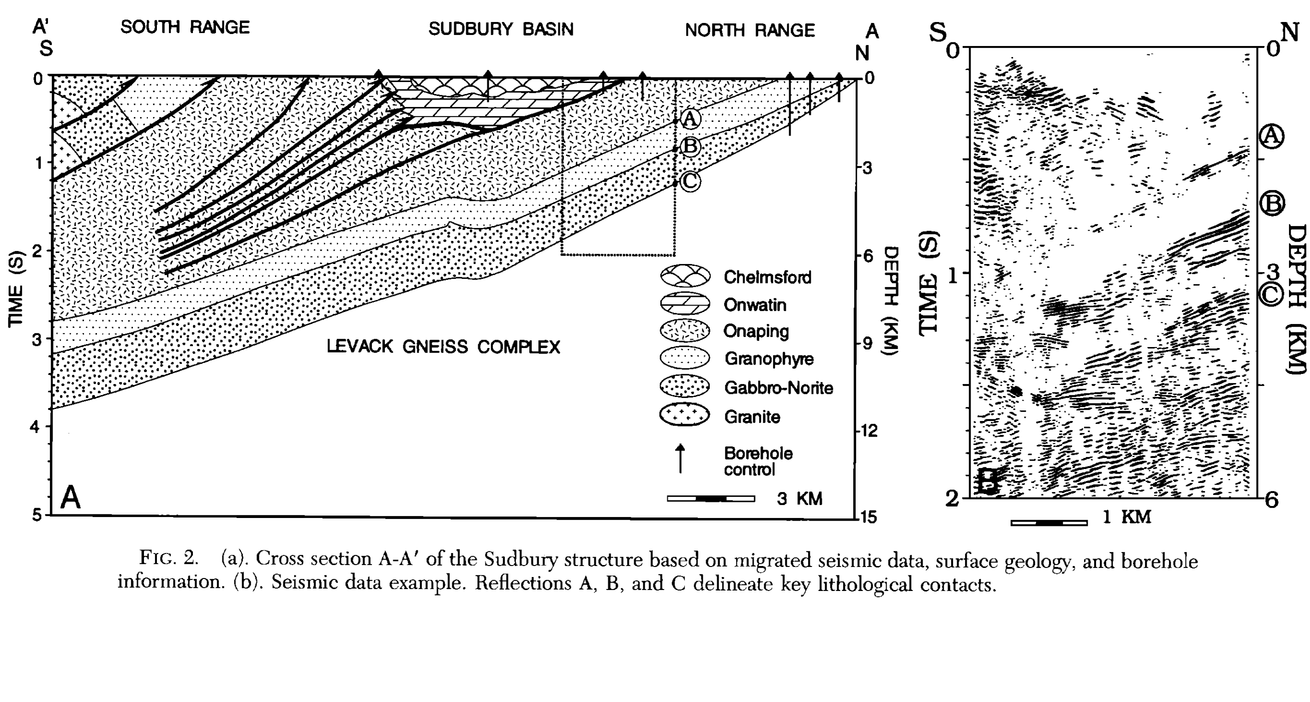

FIG. 2. (a). Cross section A-A′ of the Sudbury structure based on migrated seismic data, surface geology, and borehole information. (b). Seismic data example. Reflections A, B, and C delineate key lithological contacts.

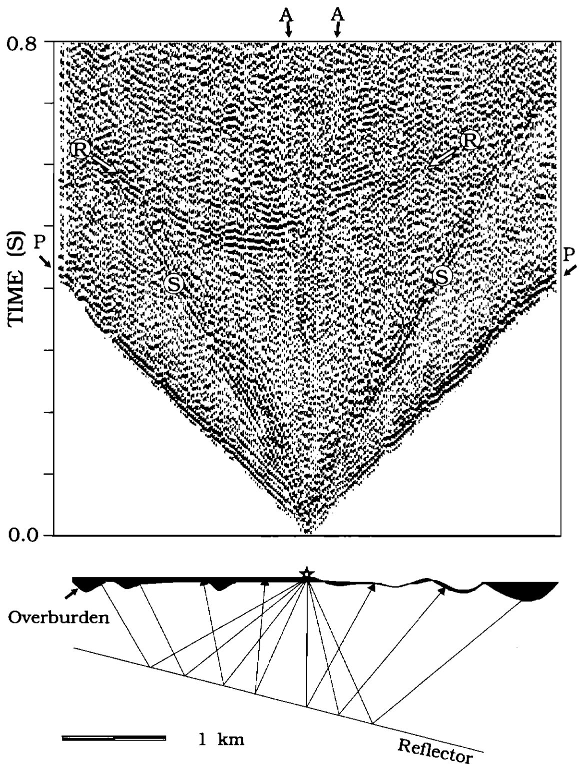

FIG. 3. Multichannel data acquisition geometry illustrating ray paths between source and receivers over a dipping reflector. Variable overburden causes travel time delays. Typically, reflections from the crystalline crust (R) exhibit a low signal to noise ratio and are often masked by ambient noise, refracted arrivals (P, S) and the air wave (A).

unconsolidated, dry glacial drift; water-saturated sediments show velocities greater than 1,500 m/s, and bedrock velocities of the Sudbury Igneous Complex are around 6,000 m/s. Static corrections were used to compensate for near-surface inhomogeneities and elevation changes.

Compared with sedimentary basins, the crystalline crust typically lacks pronounced lateral continuity of prominent seismic reflectors. For the processing and interpretation of seismic data, however, the crystalline crust introduces two important benefits: (1) a number of processing steps such as stacking velocity analysis, dip movement processing (for preservation of steep dips), and migration are simplified because of the relatively homogeneous velocity background of about 6,000 m/s; and (2) uniform rock velocities allow easy conversion of two-way reflection time to depth (i.e., a reflection at 1 s two-way traveltime is generated at ~3,000 m depth).

The final migrated seismic section across the South Range-footwall contact is shown in Figure 4a. The South Range seismic data are dominated by two steeply dipping (>45°) reflections. Reflection C-C′ is the north-dipping contact between the norite of the Sudbury Igneous Complex and the underlying footwall (comprising granite and greenstone). South-dipping reflection S-S′ projects to the South Range shear zone at the surface, a broad zone of pervasive ductile shear along which imbrication and considerable northwest-southeast shortening of the Sudbury structure has taken place (Milkereit et al., 1992b). The south-dipping shear zone approximately truncates the north-dipping norite-footwall contact at about 1.0 s (or 3,000 m). This interpretation is summarized in Figure 4b. The nature of lithologies beneath the shear zone is unknown. Clearly, the seismic image from the Sudbury South Range demonstrates the usefulness of high-frequency reflection profiling as a regional mapping tool by delineating important lithological contacts and structures at depth. In the following section, we will address the problem of detecting the discrete reflection response of a massive sulfide lens embedded in the footwall contact beneath the seismic profile.

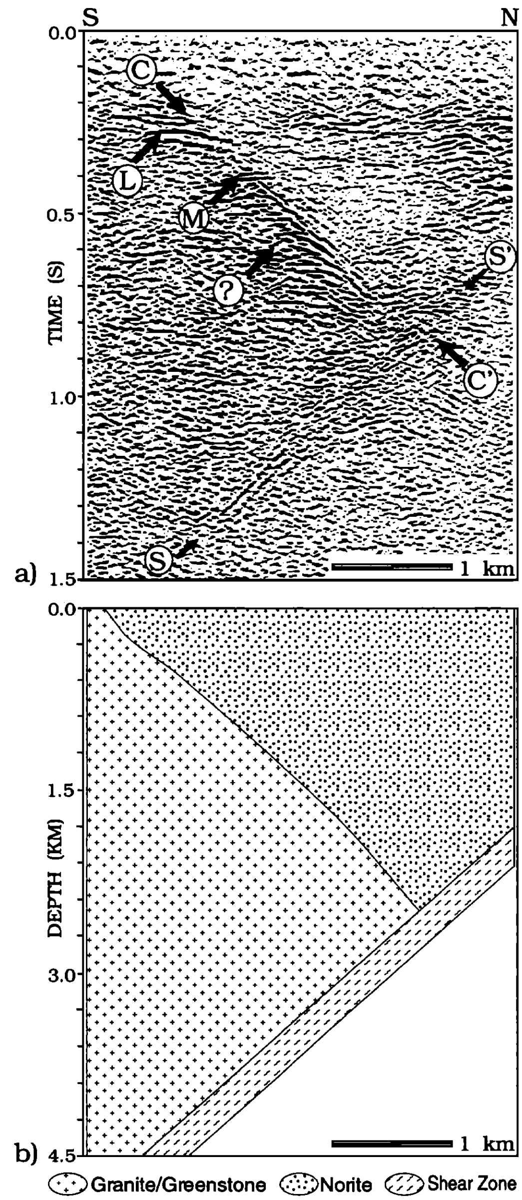

FIG. 4. (a). Migrated seismic section across the South Range of the Sudbury structure. (b). Interpreted cross section. Note north-dipping contact between norite and the footwall complex (C-C′), truncated at about a 3,000-m depth by prominent south-dipping shear zone (S-S′). No vertical exaggeration. For discussion of events "M," "L," and "?" refer to Figure 5c.

The study area, the Creighton mine, is located on the southern rim of the Sudbury basin. The mine's ores are generally located on the southeast flank of the central portion of a large topographical depression, or embayment, within the footwall of the basin. This embayment in the wall rocks is known as the Creighton trough. Noritic rocks of the Sudbury Igneous Complex are the hanging wall of the orebody, whereas the footwall rocks are a mix of mainly mafic metavolcanics of the Elsie Mountain Formation and Creighton Granite.

An inclusion-bearing zone occurs at the base of the Sudbury Igneous Complex, called the "sublayer." It is a common host for the ore and consists of a mass of basic to ultrabasic inclusions of varying size and frequency of occurrence in a matrix of norite and sulfides. When the sulfides are sufficiently concentrated, this zone constitutes the ore. The majority of Creighton orebodies are of this type. However, other types of orebodies occur as massive sulfides associated with and intruding a quartz diorite dike, as high-grade massive sulfide pods in the footwall and as massive sulfide in a variably dipping shear in the footwall. Mineralization is the usual pyrrhotite-pentlandite-chalcopyrite assemblage typical of the sublayer. The seismic line crossed above a multimillion metric ton portion of the Creighton ore known as the "402 orebody."

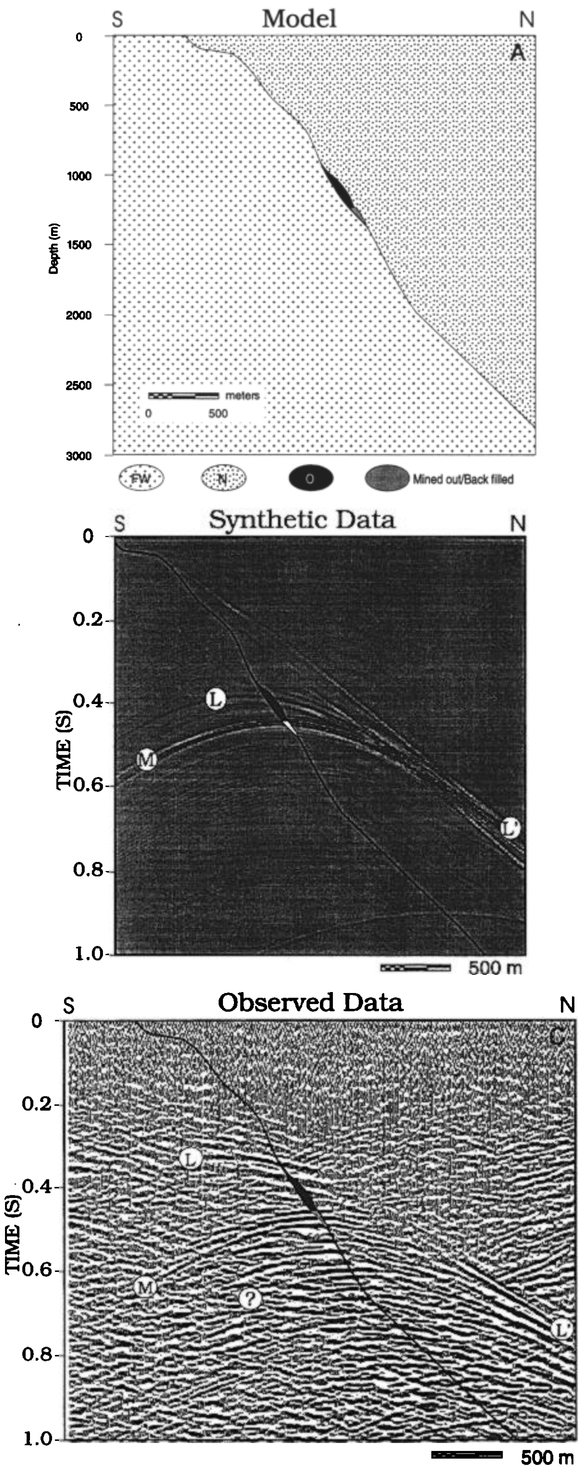

FIG. 5. (a). Two-dimensional geologic cross section of the Creighton massive sulfide deposit beneath seismic profile. FW = footwall complex, N = norite, O = massive sulfide lens (mined-out beneath 1,400 m). (b). Synthetic two-dimensional seismic reflection response based on three-dimensional geologic model of the study area. Reflection L-L′ with strong north-dipping reflections is caused by the steeply dipping massive sulfide lens, whereas the symmetric diffraction response (M) is caused by the mined-out lowermost portion of the orebody. For location, the footwall contact and orebody are superimposed on the synthetic seismic data. (c). Observed two-dimensional seismic stack section across the massive sulfide lens. The three-dimensional subsurface model accurately predicts the strong north-dipping amplitudes (L-L′) caused by the steeply dipping orebody and the symmetric diffraction response caused by the mined-out portion.

Seismic Image of a Massive Sulfide Lens

Reflection seismic profiling is ideally suited to image laterally continuous contacts and structures. The detection and delineation of relatively small massive sulfide deposits in the crystalline crust is a three-dimensional problem. Here we compute the two-dimensional seismic response of a complex three-dimensional subsurface structure and evaluate the effect of structures such as embayments and orebodies in the footwall complex on arbitrarily located two-dimensional seismic profiles. Key elements of the study are the availability of a detailed three-dimensional geologic model based on borehole data, a physical rock property database for the major lithological units, and a two-dimensional reflection seismic profile across the study area for comparison.

The detailed three-dimensional geologic model of the study area derived from exploration drilling is not shown in this paper. As indicated in Figure 4 (location shown by solid line in Fig. 1), the contact between the norite of the Sudbury Igneous Complex and granite-greenstone in the footwall dips 45° to 60° to the north. Massive sulfides are located in an embayment in the footwall. For the purpose of modeling, impedances (the product of velocity and density) were assigned to a simple three-layer model consisting of norite in the hanging wall (Z = 19), granite-greenstone in the footwall (Z = 18), and a massive sulfide lens (Z = 22) at the contact (see Salisbury et al., 1996). The size (i.e., thickness and lateral extent) of the orebody satisfies the basic requirements to be a good reflector at seismic frequencies between 30 and 140 Hz (see discussion in Salisbury et al., 1996). A simplified cross section of the geology beneath line 43 was extracted from the three-dimensional subsurface model for the area (Fig. 5a). In the study area, the massive sulfides are located between a 900- and 1,500-m depth beneath the seismic profile. At the time of the seismic experiment, the lowermost portion of the orebody, beneath the 1,400-m depth, was mined out and backfilled. In plan view the top of the orebody is located west of the seismic profile and plunges east across the line. The three-dimensional seismic model is based on a weak negative impedance contrast ($\Delta Z \approx -1$) between the norites of the Sudbury Igneous Complex and the granite-greenstones of the footwall complex. Above 1,400 m, the orebody is characterized by a strong positive impedance contrast, and below 1,400 m by an even stronger negative impedance contrast. In detail, the footwall is more complex than is shown in Figure 4a. At shallow depth, Huronian volcanics are in contact with the norite resulting in lower impedance contrasts than those predicted by the model. At greater depth, norite is in contact with granite.

Conventional ray methods are not well suited to modeling the three-dimensional seismic response of massive sulfide ore deposits in the crystalline crust since the underlying high-frequency approximation requires smooth interfaces on the scale of a seismic wavelength (i.e., several hundreds of meters). Although useful insight may still be developed by ray-tracing through smoothed models, these limitations hamper direct comparison between modeling results and actual data. Alternative seismic modeling schemes exist that are better suited for the modeling of local high impedance units such as orebodies. One of these, known as the Born approximation (Gibson and Ben-Menahem, 1991; Coates and Charette, 1993; Eaton and Stewart, 1994), can easily and efficiently accommodate three-dimensional, complex orebody and source receiver geometries. This technique predicts the seismic wave field produced by an earth model that is the superposition of a smoothly varying background medium and a short-wavelength perturbation field.

Figure 5b shows the zero-offset synthetic seismogram computed using the Born approximation. For location, the north-dipping footwall contact and orebody are superimposed on the synthetic seismic data. The synthetic response is composed of a large hyperbolic diffractionlike event (M) caused by the mined-out portion, and a series of diffractionlike events with prominent north-dipping amplitudes (L-L′) caused by the south-dipping ore lens. Note that the mined-out bottom of the massive sulfide lens causes a symmetric reflection response (M) with the strongest amplitudes centered at the cavity. In contrast, the steeply dipping massive sulfide lens causes the strongest amplitudes at a 1- to 2-km distance from the lens (in the downdip direction).

The observed stacked seismic section (Fig. 5c) is in good agreement with the synthetic seismic data shown in Figure 5b. The mined-out lower portion of the orebody generates a strong reflection (M), a diffractionlike event with the strongest reflection amplitudes observed close to the apex. The response of the intact ore is completely different. The high impedance contrast between the steeply dipping norite and ore will cause the characteristic high amplitudes of the reflection response (L-L′) to be shifted toward larger offsets in the dip direction. Figure 5c confirms that the high amplitude reflections caused by the massive sulfides can be observed over a distance which is considerably larger than the actual size of the orebody. The seismic energy is concentrated primarily in the downdip direction with the strongest north-dipping reflections observed about 1,500 m north of the sulfide lens. This observation confirms the need to acquire long continuous profiles across steeply dipping structures. Deeper reflections ("?" in Fig. 5) cannot be explained by the current simple three-dimensional subsurface model and require further investigation. Migration is intended to focus scattered seismic energy. A two-dimensional migration of the seismic profile is shown in Figure 4a. The limited spatial extent of the anomaly M beneath the seismic profile becomes apparent. The two-dimensional migration, however, cannot focus the three-dimensional scattering response of the plunging sulfide lens ("L" in Fig. 4a). Our modeling indicates that two-dimensional seismic profile can detect an orebody at depth, but a three-dimensional survey will be required to image its true shape and location.

Summary

The Sudbury experiment demonstrates, for the first time, that large massive sulfides generate a characteristic seismic reflection response. In the near future, high resolution seismic reflection profiling techniques can be tailored to image important lithological contacts and geologic structures, and to identify and delineate deeply buried, large massive sulfide deposits in the crystalline crust. Salisbury et al. (1996) discuss size and dimension criteria for the seismic method to detect massive sulfides at reasonable depth and distance. The effective use of this new exploration technique requires an integrated approach incorporating detailed knowledge of the geologic setting, comprehensive physical rock property studies, state of the art forward modeling techniques, and high-resolution seismic data sets.

The experiment also demonstrates that geologic setting and survey geometry are as critical for detection as the size, shape, and depth of the orebody. For example, the greater the dip of a lithological contact or orebody, the larger the source and receiver offsets required to record the reflected wave field. In practice, this may make it necessary to center seismic surveys in the downplunge direction away from the target. Note that surface seismic methods are best suited to imaging reflector dips up to 60°. For dips greater than 60°, borehole seismic methods should be applied (see Eaton et al., 1996).

The effect of geologic setting is difficult to quantify and we recommend that accurate forward modeling studies be applied prior to conducting a field survey. In the absence of any prior information on the geologic setting, long continuous profiles with large source-receiver offsets should be acquired in order to record the reflected wave field from dipping orebodies. Otherwise, the elected acquisition geometry will act as a powerful dip filter.

Finally, data processing requirements impose additional constraints: (1) the use of high seismic frequencies requires small separation of sensors to avoid spatial aliasing, (2) the low signal to noise ratio in the crystalline environment requires digital recording equipment with large dynamic range and high stacking fold, and (3) the need for large source and receiver offsets demands simultaneous recording of hundreds of sensors. Only recently, have state of the art exploration equipment and seismic processing techniques become available and affordable that meet these stringent requirements (Milkereit et al., 1994b).

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