DEVELOPMENT OF 3-D SEISMIC EXPLORATION TECHNOLOGY FOR NI-CU DEPOSITS, SUDBURY BASIN

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ABSTRACT

A large gap exists between the exploration depth attainable with conventional geophysical techniques, and the depth from which ore can be mined economically. The challenge was to develop a new three-dimensional mapping technique for geological exploration to depths of interest for mineral exploration. The Sudbury 3-D seismic experiment for deep base-metal exploration, the first of its kind in the world, demonstrates that high frequency 3-D seismic reflection surveys can detect and delineate deep massive sulphide deposits. This new methodology has the potential to rejuvenate deep exploration projects in mature base-metal mining camps.

INTRODUCTION AND MOTIVATION

The Sudbury Structure is located at the erosional boundary between the Archean Superior Province and the overlying sequence of Early Proterozoic continental margin deposits. The structure consists of the Sudbury Igneous Complex (SIC), a differentiated sequence of norite, gabbro and granophyre overlain by breccias and metasedimentary rocks. The Sudbury Basin is one of the richest nickel-producing areas in the world with significant accessory copper and precious metals. The SIC hosts numerous mines along its outer rim that are operated by either Inco Limited or Falconbridge Limited. Together, the two companies produced 170 000 tonnes of nickel and 160 000 tonnes of copper in 1995, representing a significant economic resource for Canada. The discovery of new deposits is vital for the continued utilization of the infrastructure of this important mining district.

The Sudbury Structure is associated with a large impact event; however, the details of the genesis of the SIC are still being debated (Boerner *et al.*, 1994). Initial exploration, based on surface prospecting and geology in the early part of this century, soon thereafter received assistance from magnetic surveys employing dip needle instruments. Starting in the late 1940s, ground electromagnetic methods were used to locate the conductive Ni-rich deposits. With these instruments, the highly conductive sulphide bodies, containing mainly pyrrhotite, could be detected to a depth of about 100 m. With modern large loop time-domain electromagnetic systems the depth of exploration was extended to about 500 m depending on the size of the target. Magnetotelluric methods are being investigated but have not yet shown that they can resolve discrete sulphide bodies at depth. However, more sulphide nickel deposits adjacent to the SIC footwall contact undoubtedly exist at depth. Therefore, there is significant interest in locating these deposits from surface, to depths of at least 2500 m, the limit at which modern mining methods are capable of economically extracting ore. Adapting seismic reflection methods to hard-rock environments may open this depth range to surface exploration (i.e., Milkereit *et al.*, 1996a).

In this paper, we present a case history for the evaluation of a new exploration technology. We review the physical rock properties of massive sulphides, discuss the seismic reflection response of deep-seated ore bodies, and present borehole geophysical data from the site selection process. Examples will illustrate various stages of the ambitious exploration project: from survey design to heliportable data acquisition and from special processing considerations to final interpretation of the 3-D seismic data volume.

PHYSICAL ROCK PROPERTY DATA

Sedimentary basins, where seismic techniques have been used most extensively, differ from the crystalline crust in a number of characteristics important for seismic data acquisition and processing (Milkereit and Eaton, 1997). Unlike most sedimentary basins, the crystalline crust typically lacks pronounced horizontal continuity of prominent seismic reflectors. In addition, the velocity structure of young sedimentary basins is characterized by low compressional wave velocities and relatively strong velocity gradients. On the other hand, the crystalline crust is characterized by uniformly high compressional velocities, in particular below 200 m where fracturing is less prevalent.

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Reflected and scattered seismic waves are generated where rocks with contrasting elastic properties (e.g., compressional wave velocity, Poisson's ratio and density) are juxtaposed. Figure 1 shows the velocity-density field (Nafe-Drake curve) for common silicate rocks ranging from unconsolidated sediments to dense, high-velocity ultramafics. Note that different applications of seismic surveys, ranging from environmental, hydrocarbon exploration, to crustal and lithospheric studies, sample different segments of the Nafe-Drake curve. For the analysis of seismic reflectivity, acoustic impedance (the density-velocity product) is the most important parameter. Acoustic impedance contrasts determine the strength of the reflected energy (i.e., contacts between lithological units of different acoustic impedances are likely to generate reflections), and curves of constant impedance are shown in Figure 1. Recently, Salisbury *et al.* (1996) demonstrated that massive sulphide ores and common mineral oxides are characterized by acoustic impedances that significantly exceed most crustal rocks, suggesting that massive oxide or sulphide bodies would make conspicuous seismic reflectors in most geologic settings. The velocity-density field for sulphides (including the pyrrhotite, chalcopyrite, millerite, niccolite and pentlandite assemblages typical for ores in Sudbury) and Fe, Ti-oxide minerals, is uniformly high and distinctly different from that for common silicate rocks. Mineral densities in composite material, containing various sulphides and silicate rocks, is governed by simple linear mixing rules (Salisbury *et al.*, 1996). Thus, the presence of sulphide minerals in the host rock will tend to define a field to the right of the Nafe-Drake curve. Depending on grade and type, base-metal deposits will make strong seismic reflectors when juxtaposed with unmineralized host rocks. The velocity-density field in Figure 1 predicts two classes of strong, prominent reflections: (1) contacts between mafic and felsic units and (2) high-density mineralisation hosted in common silicate rocks.

These two seismic marker contacts are crucial for interpreting seismic data from the hard-rock environment. At Sudbury, seismic reflections arise from lithological contacts, inferred by down-dip projections of surface geological data and drill intersections (Milkereit *et al.*, 1992, 1994a). For seismic exploration programs, the SIC mafic norite unit represents the most prominent regional "seismic marker" horizon. For mineral exploration, massive sulphides located at or close to the norite-footwall contact should produce a strong seismic reflection/scattering response. In practice several other factors, related to seismic data acquisition parameters as well as the size, shape and geological setting of the deposit, are also important in controlling the seismic response of ore bodies (see Salisbury *et al.*, 1996; Milkereit *et al.*, 1996a and Eaton *et al.*, 1996).

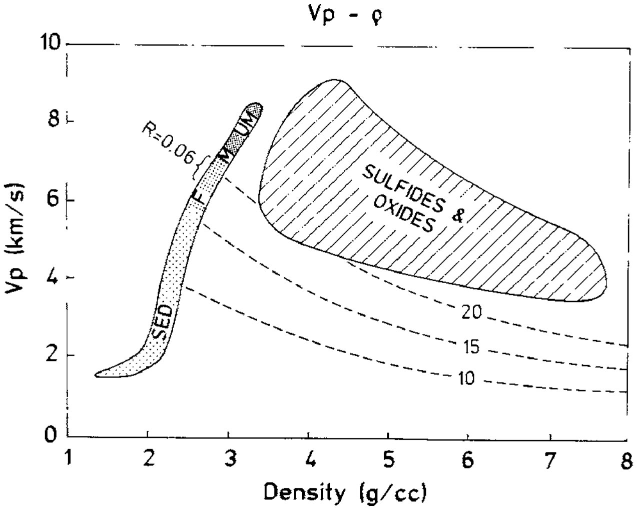


Figure 1: *Nafe Drake relation for silicate rocks with unique velocity-density fields for sulphides/oxides and lines of constant seismic impedance (modified after Salisbury et al., 1996).*

SEISMIC MODELLING OF MASSIVE SULPHIDE DEPOSITS

High density mineralization introduces problems for seismic modelling, acquisition, processing and interpretation. For seismic modelling, ray tracing is most effective if the earth can be subdivided into discrete layers separated by smooth interfaces. Ray theory breaks down if the interfaces become highly irregular, as might be the case for massive sulphide bodies and other discrete features in the shallow crystalline crust. Other techniques, such as a direct solution of the wave equation by finite-differences, are currently impractical for 3-D seismic modelling. In this study we apply the 3-D Born-Approximation (Eaton, 1996).

The Born Approximation is designed to handle geological situations where short wavelength impedance anomalies (such as ore bodies) are embedded in a smoothly varying background medium. Consider the case of a dipping-lens model consisting of a 200-m wide, disk-shaped high-impedance unit at 1000 m depth. The background velocity is 6000 m/s. Figure 2 shows the zero-offset scattering response from such a feature, inclined at 45°. The unmigrated data show the region over which the diffracted energy is visible, which is considerably larger than the actual size of the scattering body. After migration, the true spatial extent of the anomaly becomes apparent. In the unmigrated data, scattered energy is concentrated primarily in the down-dip direction. It is worth noting that for mineral exploration the strongest reflection amplitudes of the scatterer often develop in the dip direction, away from the target. In contrast to reflections from continuous interfaces, the scattering response from local heterogeneities remains stationary (i.e., the travel-time response is symmetric with respect to the location of the scatterer in the 3-D cube) (Milkereit *et al.*, 1996b).

Because of the inherent limitations of conventional seismic modelling methods, the strike- and dip-related characteristics of small seismic energy scatterers may not have been fully appreciated in the past. (Most conventional 2-D seismic reconnaissance profiles may have overlooked or underestimated the significance of local bright seismic amplitudes caused by density anomalies.)

Most local density anomalies are 3-dimensional features (often lens- or disk-like); commonly these volume anomalies are not tied to any simple layered structure. Such geometry presents additional difficulties for data seismic processing. (Continuous reflection elements are not available to guide stacking velocity analysis, deconvolution and filter tests as well as migrations.) In addition, to detect accurately and delineate local high impedance bodies requires 3-D seismic surveys.

SPECIAL PROBLEMS POSED BY THE HARD-ROCK ENVIRONMENT

In the past, tests of high resolution seismic imaging methods, utilizing "off-the-shelf" technology from hydrocarbon exploration, have met with limited success. High levels of source-generated noise in the 10- to 30-Hz range can overwhelm the relatively weak reflected signal. Perhaps the most fundamental distinction, however, stems from unanticipated differences in the statistical properties of reflection coefficient time series (Milkereit and Eaton, 1997). Analysis of power spectra derived from borehole data in crystalline terranes, indicates a systematic enhancement of higher frequencies relative to spectra commonly observed in sedimentary basins. This fundamental difference must be accommodated in the design of 3-D seismic surveys to fully characterize the response of the subsurface.

In practice, spatial aliasing and the number of recording channels limits the design of 3-D seismic surveys, including

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,
3. the need for large source-receiver offsets to facilitate recording reflections form dipping structures demands simultaneous recording of thousands of sensors.

Although high frequency seismic data should provide excellent resolution, special attention must be given to data acquisition and processing if the bandwidth and resolution are to be preserved. As well, unfavourable near-surface conditions at the source or receiver may attenuate high frequencies.

While results from 2-D reconnaissance seismic profiles acquired across the Sudbury Basin (Milkereit *et al.*, 1992, 1994a, 1996a) have provided important information on gross structure and regional geological setting, there have been problems integrating this new mapping technique into normal exploration procedures. For example, borehole geophysical logs (i.e., density and sonic velocity), important for the interpretation and calibration of reflection seismic data, have not been acquired routinely in existing slim (50 mm diameter) diamond drill holes. Over the past three years in the Sudbury region, an extensive database of geological mapping information, geophysical logs of existing deep drill holes, and core samples for physical rock property studies has been assembled to support interpretation of the surface seismic data (Milkereit *et al.*, 1994b).

3-D SEISMICS FOR MASSIVE SULPHIDE EXPLORATION

In 1993, a 2-D high-frequency vibroseis profile was acquired across the South Range of the SIC (Milkereit *et al.*, 1996a). The profile traversed a large, thick pyrrhotite body which lies approximately 900–1500 m below the surface. Actually locating this sulphide deposit at relatively great depth with surface seismic methods was a significant result and encouraging enough to continue with further research. The detection and delineation of relatively small massive sulphide deposits in the crystalline crust, however, is a three-dimensional problem (see Eaton *et al.*, this volume). Until recently, the vast majority of seismic surveys have utilized 2-D profiling, where source and receiver locations are collinear, as the basic acquisition geometry. This approach essentially yields vertical cross-sectional images of the subsurface, and is most effective where major structural and stratigraphic elements have a well defined strike direction and the 2-D seismic profiles can be oriented perpendicular to regional trends. If the subsurface structures do not have a well defined strike and dip direction, out-of-plane reflections (sideswipe) can seriously contaminate 2-D reflection images, producing false structural images. The spatial dimensions of economically viable ore bodies embedded in complex crustal structures ("the needle in the haystack") make them unlikely to be detected in the course of reconnaissance 2-D seismic work. For these reasons 3-D reflection seismic surveys should be considered for mineral exploration.

TRILL 3-D SEISMIC EXPERIMENT

At Sudbury, 2-D seismic profiles were acquired along existing roads or trails. For 3-D seismic surveys in remote areas, limited access makes it impossible to rely on Vibroseis sources. Instead these surveys must utilize small explosive charges in shallow drill holes. Extensive tests were required to optimize source parameters (i.e., bandwidth and dynamic range) for off-road 3-D seismic exploration programs. A feasibility study was initiated to choose a suitable location for the first 3-D seismic survey. The feasibility study was accompanied by detailed 3-D forward modelling studies to address the "technological challenges" of detecting and delineating ore in a complex geological setting between 1 and 3 km depth. For example, the SIC is characterized by moderate dips (30–60°), homogeneous high velocities (>6000 m/s) and low signal-to-noise ratios. Thus, high frequencies of about 100 Hz must be generated by the seismic sources, recorded by the receiver grid, and preserved throughout the processing sequence.

SITE-SELECTION PROCESS

Results from 2-D profiling, physical rock property studies and forward modelling provided strong support for the hypothesis that massive sulphide bodies are detectable by their characteristic scattering response in

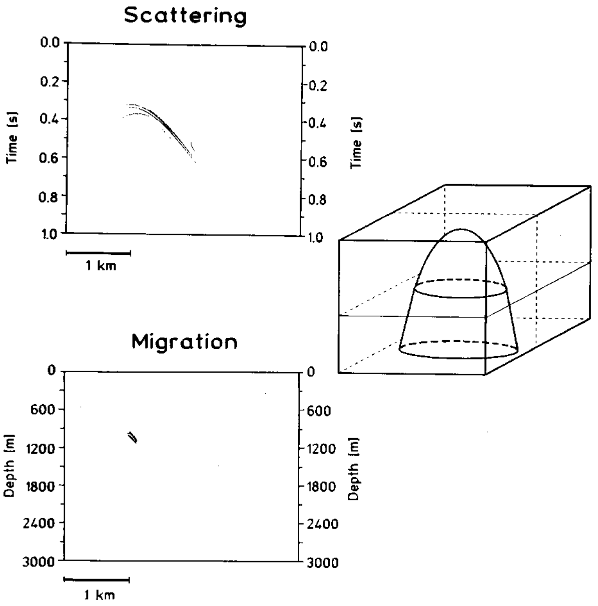


Figure 2: *Top: Scattering event caused by a local high impedance contrast (a dipping lens at 1000 m depth). Note the asymmetric zero-offset response. Bottom: Migration of zero-offest section.*

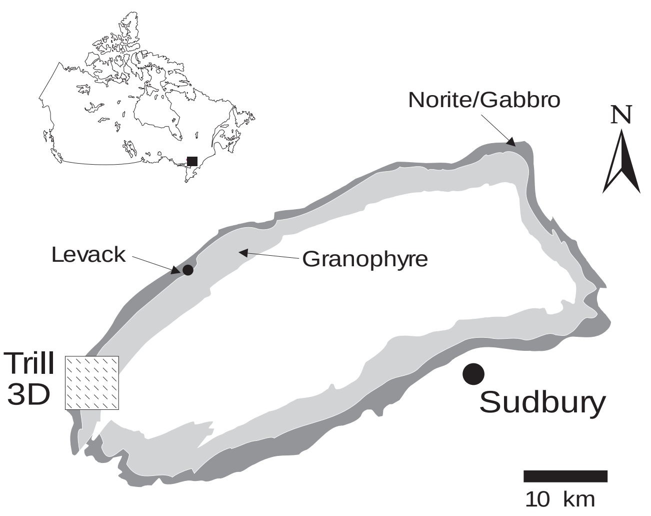


Figure 3: *Location map of the Trill 3-D survey in the Sudbury Structure.*

a 3-D seismic data set. In the spring of 1995, it was decided to enter into a comprehensive site-selection process (Table 1) for the first 3-D seismic survey for mineral exploration in North America. Borehole geophysical logging, vertical seismic profiling (VSP) and seismic source strength evaluations were conducted in the Trill and Levack areas of the Sudbury North Range (Figure 3).

Small explosive charges (from 0.05 to 1.0 kg) in shallow boreholes were used as the sources for VSP and noise spread surveys. The seismic data recorded by stationary surface geophone spreads and downhole three-component seismometers were analyzed for bandwidth, dynamic range and geometrical spreading of the signal. Source depth tests were required to evaluate waveform consistency and to minimize source-generated noise (in particular, shear wave energy).

At the same time, a geographic information system (GIS) was built for the study areas. Special emphasis was placed on the availability of digital topography, surface geological maps and borehole data (depth to footwall contact) to conduct a detailed simulation of the proposed 3-D seismic experiment. In parallel, environmental assessment/impact studies were conducted and line-cutting, drilling and seismic data acquisition contractors were selected.

In situ physical property measurements are necessary for the conversion of reflection times to depth and to understand fully the cause of seismic reflectivity. The logging and borehole seismic experiments were conducted with slim full waveform sonic, γ-γ density and three-component seismic tools in selected NQ- and BQ-diameter holes. At Trill and Levack, density and velocity data were recorded to about 1800 m depth. Figure 4a shows density and velocity logs from the Trill site. SIC norite has a narrow range of velocities, varying from 6200 to 6400 m/s, while the sublayer and footwall complex exhibit highly variable velocities in the range of 6000 to 6700 m/s. The in situ densities follow the same trend as the P-wave velocities: relatively uniform densities between 2.75 and 2.8 g/cm^3 are associated with the norite, while densities of the sublayer and footwall complex are scattered between 2.75 and 3.0 g/cm^3.

In situ studies in deep boreholes confirm that significant impedance contrasts exist at the contacts between major lithological units of the SIC and the footwall complex (Figures 1, 4a). The sublayer at the base of the SIC is a host for the ore. The sublayer consists of a mass of basic to ultrabasic inclusions of varying size and frequency of occurrence in a matrix of norite and sulphides. When the sulphides are sufficiently concentrated this zone constitutes the ore. Important for the direct seismic mapping of ore bodies is a knowledge of impedance values (controlled by velocities and densities) for disseminated and massive sulphides. In Figure 1, we demonstrated that the ores occupy a density-velocity field which is distinct from that of common silicate rocks and governed by simple mixing rules between the properties of host rocks and end-member sulphides. The density measurements from core samples (Figure 4b) confirm that sulphide samples from the Trill study area occupy a distinct velocity-density field to the right of the Nafe-Drake curve. The presite surveys confirm that the pyrrhotite-rich ores are characterized by high impedance values.

Because borehole intersections with the footwall complex are unevenly spaced, the depth-to-footwall data (Figure 5b) were gridded and a linear trend was introduced to preserve the regional steep dip of the footwall contact in regions where there is little or no data. At Trill, the important contact between the SIC norite and the footwall complex dips 30–60°. From surface and borehole data, it is difficult to define a single strike direction for the study area.

Massive sulphides are located in an embayment in the footwall. In map view, the top of the deep mineralization is located at about 1800 m depth in the centre of the survey area.

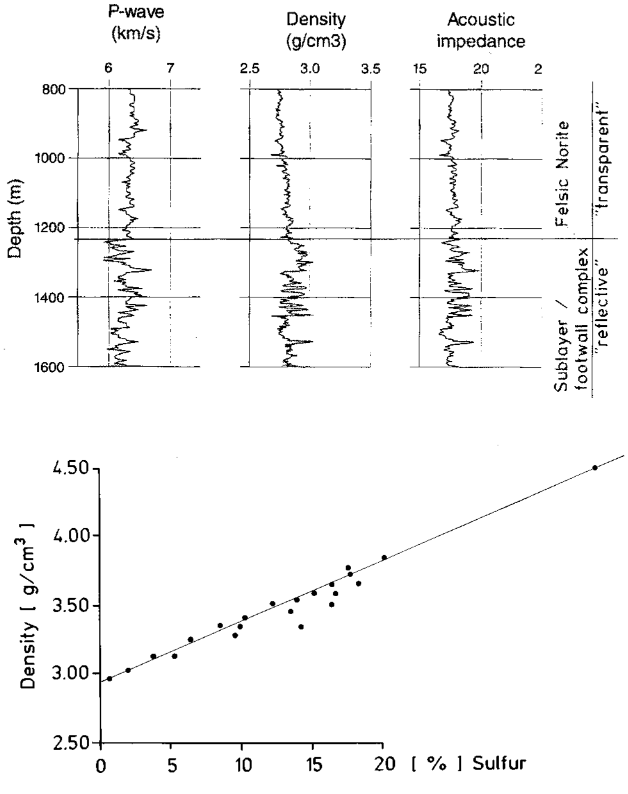


Figure 4: *(**a**) Borehole logs from the Trill study area. (**b**) In situ densities of sulphides compiled from assay data (Trill area).*

3-D seismic data acquisition differs from 2-D seismic surveys in terms of the layout of sources and receivers. Figure 5a shows the actual (final) layout for sources and receivers. At Trill, receiver lines are oriented east-to-west, perpendicular to the grid of shot lines. Details about the source-receiver geometries are given in Table 2. After collecting the data from all of the sources (1050), the data are sorted into bins with dimensions of 20x20 m during data processing, defining the ultimate resolution limits of the final migrated image. This is illustrated in Figure 5c, a fold diagram for this survey which shows that the area of full fold coverage (greater than 30) is smaller than the full survey area.

The results of the feasibility study (Table 1) determined that the Trill area would be one of the best locations for a 3-D seismic survey to locate massive sulphides for mineral exploration. The area has low noise levels (no trains, no pipelines and no high voltage power lines) and with the availability of a well defined target at about 1800 m depth and a respectable borehole database, enough information is available to evaluate the performance of this new exploration technology. In addition, the 3-D seismic data could provide new information about the deep geology and associated mineral deposits of the area.

In summary, the objectives of the 3-D survey at Trill were three-fold: (1) to image the moderately to steeply dipping contact between the norite and the footwall complex, (2) to detect a seismic response from the known massive sulphides at depth, and (3) to integrate physical rock property, seismic and drill hole data.

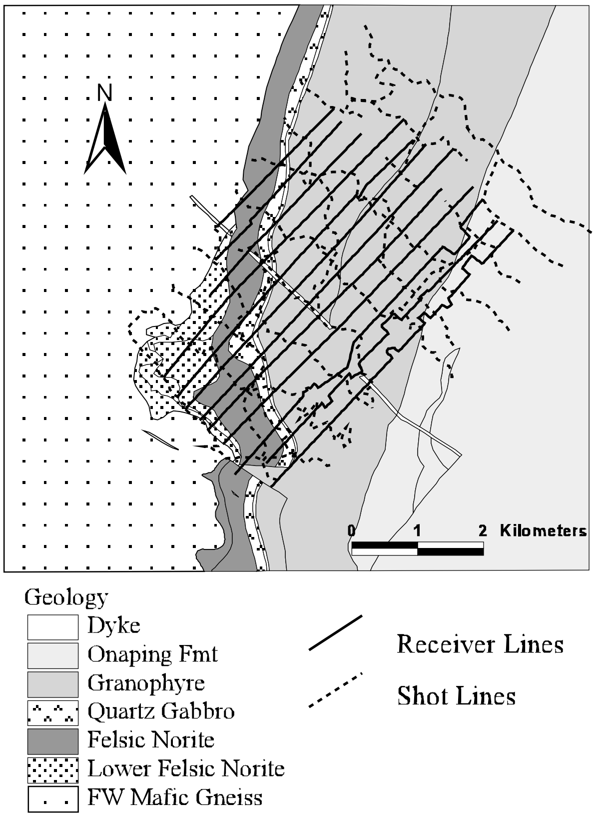
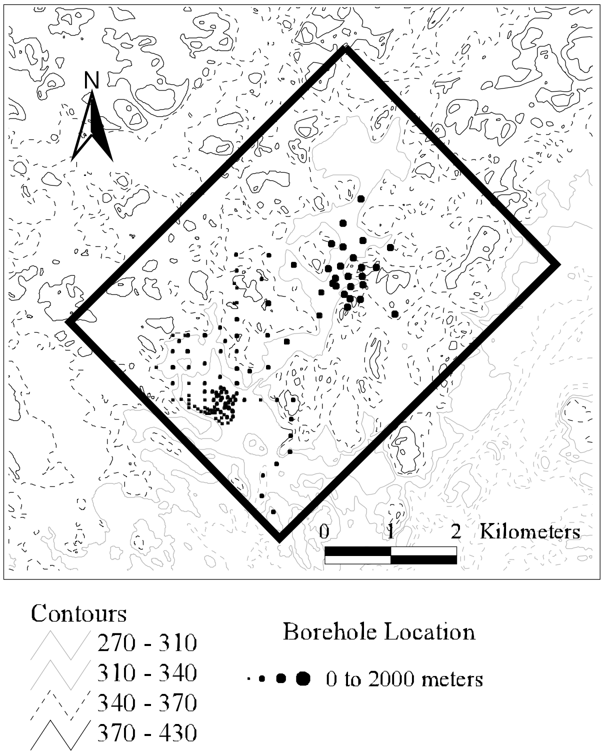


Figure 5a: *Trill geology with survey grid.*



depth to footwall.

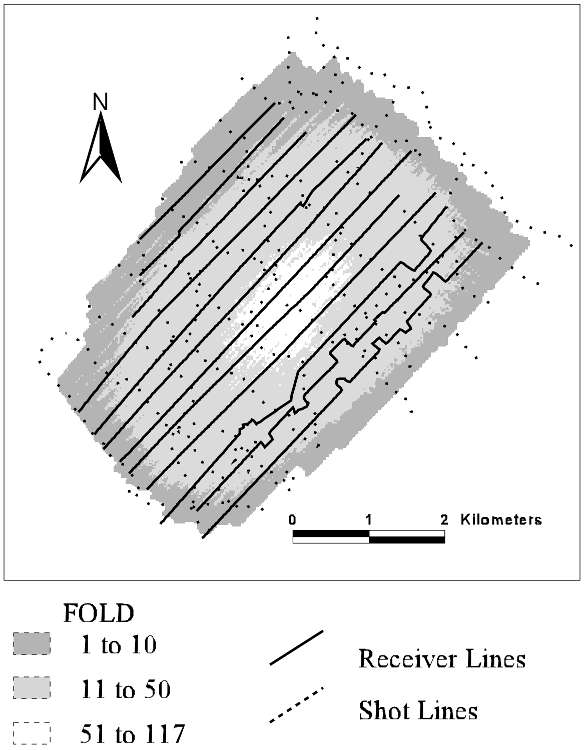


Figure 5c: *Fold diagram based on actual source and receiver locations.*

Table 1: ***Preparatory steps***

1.1 Conduct slimhole surveys of
  - existing boreholes
  - velocity logs
  - density logs
  - vertical seismic profiling

1.2 Acquire surface recordings (noise spreads)
  - evaluate charge size (0.05 to 1.0 kg)
  - determine charge depth (up to 10 m)
  - evaluate noise sources

1.3 Build GIS of study area, compile
  - depth to footwall contact (from borehole database)
  - digital topography
  - surface geology
  - physical rock property data

1.4 3-D Forward modelling of survey area
  - compute 3-D synthetic response
  - test processing parameters
  - evaluate resolution
  - adjust source and receiver geometries

1.5 Other considerations
  - access to study area
  - access within study area
  - quality of presite surveys (logs)
  - noise (man-made, ambient)
  - restricted areas (trout streams, escarpments)
  - 3-D geological subsurface model (dips $< 60°$)
  - overburden conditions (static corrections, shot coupling)

1.6 Final evaluation
  - rank potential sites for 3-D survey
  - obtain necessary work permits (environmental assessment)
  - update cost estimates

Table 2: ***Data acquisition parameters***

2.1 Original survey parameters
  - survey area approx. 30 km^2
  - 15 × 30 m subsurface bin size
  - 13 receiver lines
  - 30 m receiver station spacing
  - 300 m receiver line spacing
  - 6 source lines
  - 50 m source point spacing
  - 600 m source line spacing
  - 1050 shot points (0.25–0.5 kg in 5–10 m deep holes)

2.2 Instrumentation
  - 2000-channel, 24-bit telemetry system
  - I/O System II, all channels live
  - high Cut Filter: 270/188 Hz
  - pre-amp Gain: 36 dB
  - geophone Type: Mark L-210 (marsh phone)
  - geophone Array: bunched
  - 3-component downhole geophone SIE T42 locked at 1070 m depth
  - Hughes 500 D helicopter for deployment and pick-up of equipment

SURVEY DESIGN AND FIELD OPERATIONS

The Trill area is characterized by steep hills, extensive swamps and limited access. As discussed earlier, the final 3-D survey design was based on detailed 3-D forward modelling of the Trill area and operational constraints. The GIS database supported the pre-survey 3-D modelling of the Trill area through a simple 3-D geological subsurface model. We used the 3-D Born modelling approach (Figure 2) to accommodate the complex shape of the contact between SIC and the footwall complex, known mineralization at 1800 m depth, and source-receiver geometries used for the actual seismic experiment. The resulting synthetic data were processed and migrated to obtain a realistic approximation to the anticipated seismic processing sequence. Synthetic models indicated that the steep dips and deep targets would necessitate additional shot points at the southeastern corner of the study area. In addition, modelling of the scattering response of deep massive sulphides predicted a unique amplitude-versus-offset (AVO) signature. It was predicted that large source receiver offsets (up to 6000 m) would be required to support the AVO analysis, and as a result, the design of the seismic data acquisition program was modified. As well, additional shot points were needed to compensate for irregular source and receiver line spacing due to swamps, lakes and rough topography. The Trill study area with 12 receiver lines and 14 source lines is shown in Figure 5a.

The recording crew mobilized to the project in late October 1995. Wet weather in the Sudbury area made many of the receiver lines difficult to walk, and water levels rose in the swamps and creeks. During the chaining, surveying and equipment lay-out crews were forced to use hip-waders, canoes and boats to a much greater extent than had been anticipated.

During start-up tests, temperatures dropped, ground froze and lakes became ice-covered. Receiver spacing of 30 m was used to give a nominal fold of 30, marsh phones being used to guarantee good coupling in swamps. A project this size (2,003 live receiver stations) is large by industry standards and it was difficult to keep all stations operational, particularly in rough terrain (with numerous beavers continuously gnawing on cables). Deployment and retrieval of the recording equipment was made possible through the use of a Hughes 500 D helicopter. Data were collected using a 2000-channel telemetry acquisition system. Nine days were required to deploy the recording spread. Recording the 1050 shot points, however, was completed within 30 hours. Equipment pick-up was delayed by frozen cables and geophones. In addition, the first snow storm hit the Sudbury area just hours before completion of the equipment pick-up.

A three-component seismometer was placed in a deep borehole (at 1070 m) near the centre of the study area and recorded all shots. This borehole seismometer proved to be a valuable tool for quality control and data editing, and confirmed that small seismic sources in thick, dry overburden do not produce sufficient energy for reflection seismic studies. In contrast, small charges in bedrock do. During data acquisition in the hardrock environment, it is not common to observe clear, high quality reflections in "raw" shot records because of source-generated noise (strong shear waves and low frequency noise from flowing water). In data processing, bandpass filtering and a high stacking fold are required to attenuate these types of noise. The shots recorded by the three-component borehole seismometer revealed a strong amplitude anomaly in the vicinity of the borehole. For better comparison with surface seismic data, the shot records are plotted with direct P-wave and S-wave energy muted.

Figure 6 shows an east-westsection across the borehole location. Note the strong reflection/diffraction event at 0.6 s. Generally speaking, seismic data quality (bandwidth and dynamic range) exceeded our expectations.

PROCESSING OF THE TRILL 3-D DATA SET

The data processing sequence had to take into account the highly variable overburden conditions (deep swamps, thick eskers, basement outcrop, and rough topography) as well as steeply dipping (>45°) geological structures. The final processed 3-D data cube covers an area of 24 km^2 and consists of 200 east-west lines and 301 north-south lines; the lines are separated by 20 m. Details are given in Table 3.

First results appeared "blurred" and it appeared that conventional 3-D seismic data processing strategies were not well suited to handle weak seismic signals from individual scatterers in the crystalline crust. Various data processing options were evaluated and a robust processing sequence was developed, which consisted of a rigorous computation of weathering static corrections, deconvolution, time-variant band-pass filtering and stacking velocity analysis. Various 3-D data binning and stacking schemes were also tested. Once strike and dip were determined, stacking with restricted azimuthal coverage was used for stacking velocity analysis. The evaluation of various 3-D stacked sections revealed that a limited azimuth stack provided the most robust results (sufficient bandwidth and dynamic range). A number of image enhancement techniques (3-D deconvolution) and poststack depth migration schemes were tested.

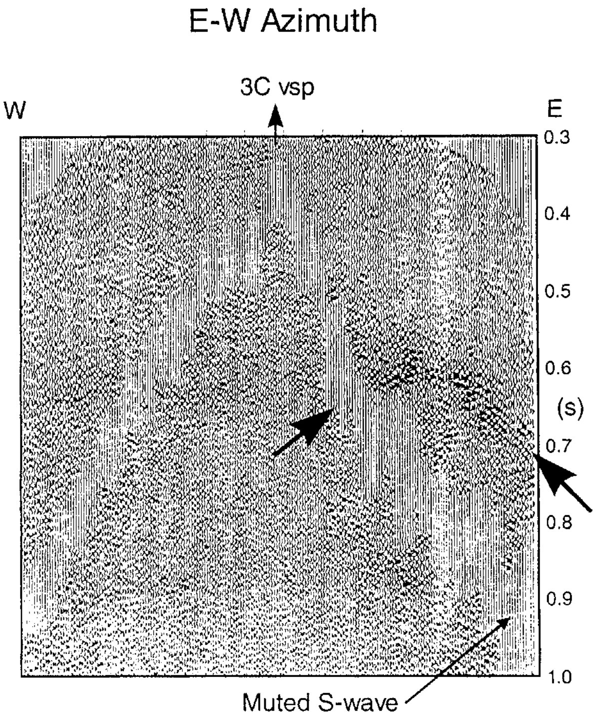


Figure 6: *Borehole seismic image (based on "walk-away" source-receiver geometry) recorded by downhole seismic sensor at 1040 m depth during the 3-D data acquisition program. Note local amplitude anomaly (marked by arrows).*

Table 3: ***Processing and interpretation***

3.1 Brute stack and parameter tests
- verify geometry
- edit shots and receivers
- compute static corrections (datum: 350 m above sea level)
- select deconvolution, filtering and scaling
- 3-D binning (15 × 30 m bins)
- stack
- revise strike and dip estimates
- evaluate 3-D dip moveout (DMO) processing

3.2 Final stack
- revise geometry
- 3-D binning (20 × 20 m bins)
- high pass filter: 30 Hz
- evaluate azimuthal coverage
- stacking velocity analysis
- stack
- poststack amplitude scaling
- poststack deconvolution
- one-pass 3-D phase-shift migration (6300 m/s)

3.3 Interpretation (workstation) stacked volume:
- identify scattered events
- display selected scatterers

migrated volume:
- pick top sublayer reflection
- pick top footwall reflection
- integrate borehole database
- revise interpretation
- display horizon maps

For the steep dips in the Trill area, one-pass 3-D phaseshift depth migration (assuming an average velocity of 6300 m/s)provided excellent results (Figure 8). Finally, stacked and depth-migrated 3-D data cubes of the study area were interpreted utilizing 3-D interpretation workstations. The stacked and migrated seismic volumes, supporting borehole data, survey information and interpreted horizon maps were archived on CD-ROM.

3-D SEISMIC DATA INTERPRETATION

The Trill 3D seismic survey provides new insights into the deep structure of the North Range of the SIC. Local high impedance contrasts such as massive sulphides cause scattering of seismic energy (Figure 2). At Trill, prominent circular and semicircular scattering events are observed in horizontal (time) slices of the 3-D seismic data. The strongest events occur at about 0.6 s two-way reflection time (about 1800 m depth). This sequence of events in Figure 7 is centred above the known mineralization and can be traced from 590 ms to about 700 ms like expanding ripples in a pool. The data confirms the forward modelling shown in Figure 2. A high impedance contrast between the steeply dipping norite and the footwall complex causes the characteristic high amplitudes of the reflection response to be shifted towards larger offsets in the down-dip direction. The strongest east-dipping reflections are seen about 1000 m east of the known mineralization (marked in Figures 7a-d), a distance which is considerably larger than the actual size of the ore body. The interpre-

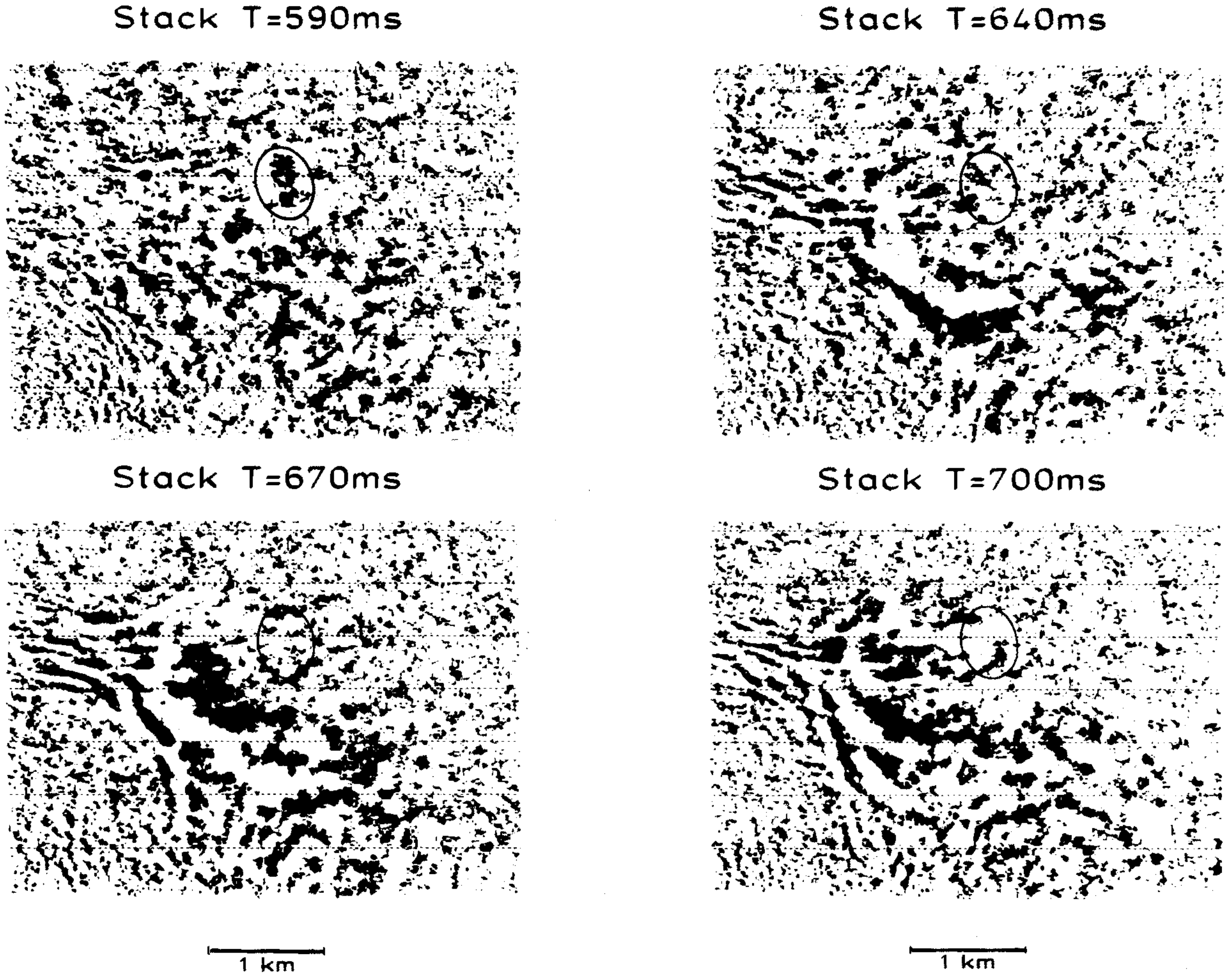


Figure 7: *(**a-d**) Sequence of time slices through the stacked 3-D data cube; the known mineralization (ellipse) is located at about 1800 m depth (about 590 ms reflection time assuming an average velocity of 6300 m/s). At 590 we observe a weak circular reflection event; the event expands and at 640 ms, a high amplitude semicircular reflection develops towards the east. Despite interference from footwall structure and other events, the semicircular event continues to grow later in time (slices at 670 and 700 ms).*

tation of the scattered energy is complicated by the fact that other "scatterers" located northeast and southwest of the known mineralization interfere at a later time. In addition, the phase and amplitude of the scattered wavefronts are not constant, causing severe amplitude-versus-azimuth (AVA) variations.

Interpretation of the seismic data should "honour" the available borehole data (Figure 5b) and geophysical logs (for example, Figure 4a). The database consists of borehole locations and associated "depth to footwall contact". Migrated sections were used for the interpretation of dipping lithological contacts. As predicted by the borehole geophysical logs shown in Figure 4, the footwall contact and the top of the sublayer are well imaged between 1000 and 2500 m depth (Figure 8). The strike and dip of these two units change laterally within the study area. Towards the east, the footwall contact forms a local embayment structure at about 2000 to 2500 m depth (Figure 9). In the east, the interpreted sublayer thickness reaches its maximum. Towards the south, the sublayer thickness decreases and "reflectivity" in the footwall of the SIC increases. These deeper reflections within the footwall complex cannot be explained by the available geological and geophysical logs and require further investigation.

The main results of the Trill survey are summarized in Figure 10. The perspective view (from the east) shows the steeply dipping footwall contact, the location of the known mineralization, and the scattering response (a time slice through the stacked volume at 652 ms) caused by the mineralization.

SUMMARY AND CONCLUSIONS

Following presite surveys, the Trill area was selected for conducting North America's first 3-D seismic survey for base-metal exploration. The 3-D seismic experiment confirms that even in a difficult geological

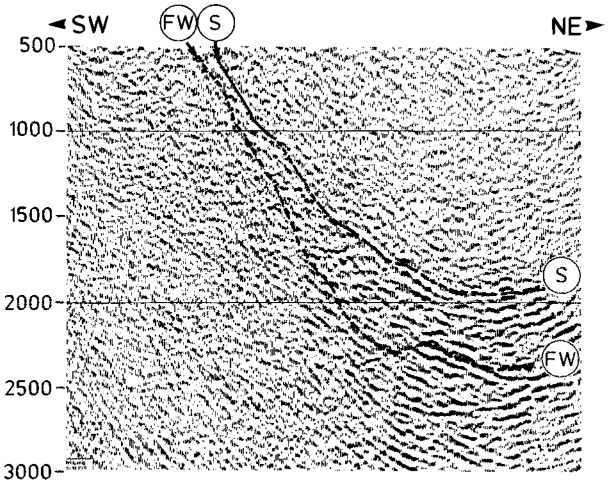


Figure 8: *Migrated section with interpretation overlay (sublayer and footwall complex). The Sudbury Igneous Complex above the sublayer reflection is seismically transparent (compare with borehole logs in Figure 4a).*

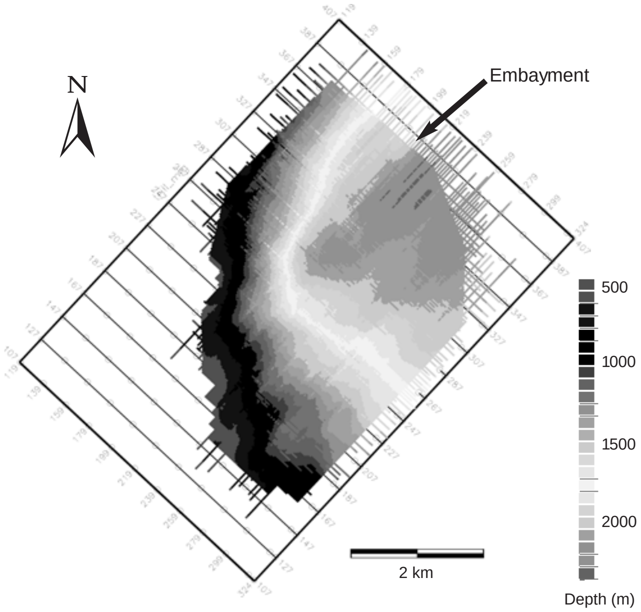


Figure 9: *Horizon map derived from migrated data. The depth to footwall shows a pronounced embayment structure.*

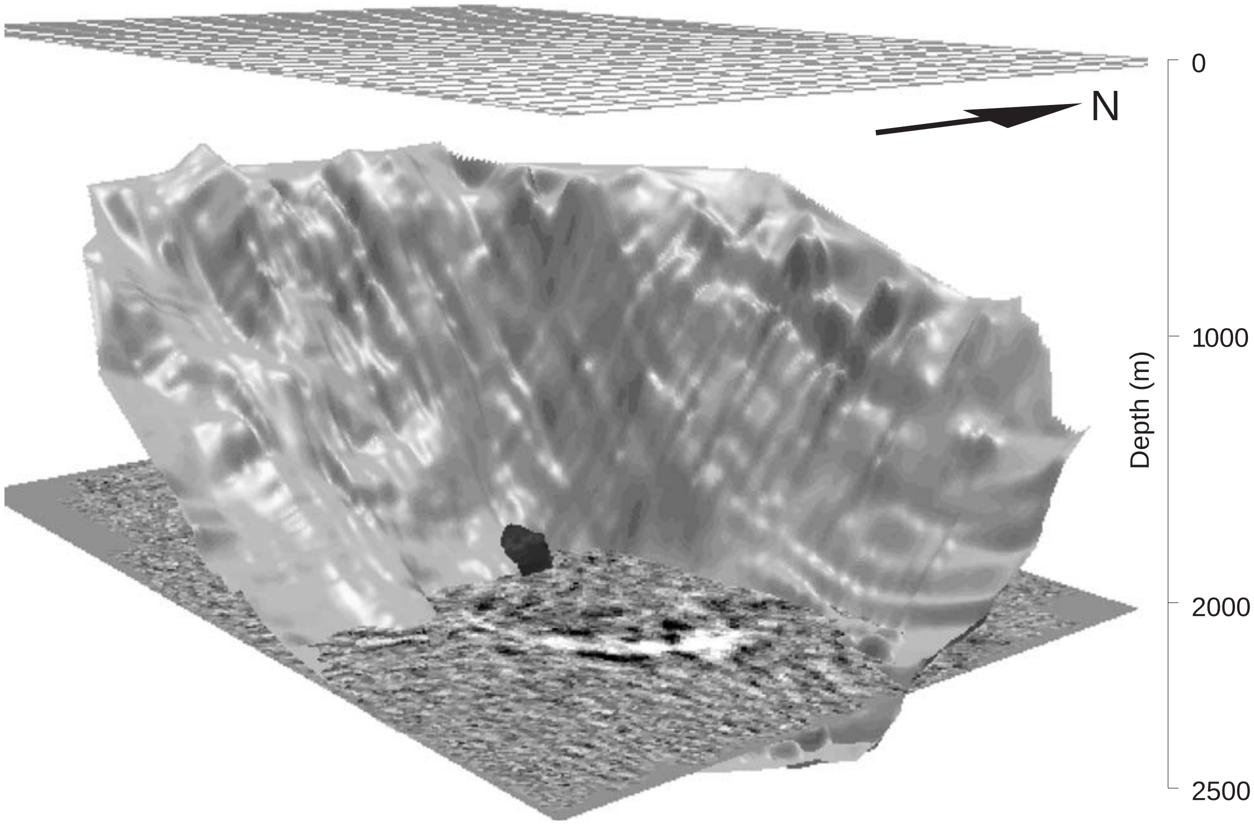


Figure 10: *Perspective view of interpreted footwall contact (contoured surface of Figure 9), known mineralization at 1800 m depth (black oval shape), and scattering event caused by the mineralization (time slice at 652 ms).*

setting such as the Sudbury North Range, massive sulphide bodies cause a characteristic and identifiable seismic scattering response.

This provides an excellent basis for the direct detection of massive sulphides by seismic methods. The feasibility study suggests that high resolution seismic methods offer a large depth of detection, on the order of hundreds to thousands of metres. At Sudbury, seismic methods are ideally suited to map the contact between the "transparent" lower SIC and its "reflective" footwall complex.

The detailed 3-D modelling studies demonstrate that geological setting and survey geometry are as important for detection as the size, shape, and depth of the ore body. For example, the greater the dip of a lithological contact or ore body, the larger the source-receiver offsets required to record the reflected wavefield. In practice, this may make it necessary to centre 3-D seismic surveys in the down-plunge direction away from the target.

A preliminary assessment of the Trill project points towards current strengths and weaknesses of the new approach of 3-D seismic exploration technology for the crystalline crust. Data acquisition and interpretation strategies can easily be modified from well established parameters used for oil and gas exploration in sedimentary basins (Milkereit and Eaton, 1997). For example, the seismic bandwidth must be extended to higher frequencies. State-of-the-art, multi-channel telemetry data acquisition systems and off-the-shelf GIS and 3-D seismic interpretation workstation environments offer adequate solutions. Current hydrocarbon-industry standard seismic data processing strategies, however, often fail to produce acceptable results. Special attention must be paid to improved static corrections in order to enhance images of seismic scatterers. In addition, velocity and density logs must be obtained for detailed interpretation and calibration of 3-D seismic images. The integrated seismic studies in Sudbury demonstrate, for the first time, that a massive sulphide ore body can generate a characteristic seismic reflection response.

By adjusting acquisition and processing parameters, high frequency seismic reflection profiling techniques can be tailored to (1) image important lithological contacts and geological structures (such as embayments [Morrison, 1984]) and (2) identify and delineate deeply buried, large massive sulphide deposits in the crystalline crust. The effective use of this new exploration technique requires an integrated approach incorporating detailed knowledge of the geological setting, comprehensive physical rock property studies, state-of-the-art forward modelling techniques, and high-resolution seismic data sets. 3-D reflection seismic profiling could support new deep exploration projects in existing and prospective sites as well as prolong the life of established mines in the Sudbury Basin.

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Geological Survey of Canada contribution.

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