3-D Seismic Exploration

Eaton, D.W.[1], Milkereit, B.[2], and Adam, E.[3]

1. Department of Earth Sciences, University of Western Ontario, London, Ontario, Canada
2. Institute of Geophysics, Christian-Albrechts-University, Kiel, Germany
3. Continental Geoscience Division, Geological Survey of Canada, Ottawa, Ontario, Canada

ABSTRACT

Three-dimensional (3-D) seismic exploration is a geophysical technique that has undergone rapid growth and development in the petroleum industry. It is a mature technology that has the potential to provide accurate volumetric images of the subsurface for interpreting the structural and stratigraphic framework of ore deposits. Under favourable circumstances, 3-D seismic methods can also provide direct delineation capabilities for large, deep-seated ore bodies.

The 3-D seismic method involves the acquisition of seismic data on an areal grid. Processing and interpretation techniques exploit the dense subsurface sampling provided by the 3-D data volume. Some modifications to standard practice are required, in view of the complex scattering and weak reflectivity that characterizes seismic data from crystalline terranes. Critical steps in the processing sequence are those used to correct for variable near-surface conditions, attenuate noise, and re-position (migrate) reflections into their true subsurface configuration. Interpretation of the data is typically carried out on a computer workstation, using specialized software that permits efficient horizon picking, display of the data in vertical and time-slice orientation, and volume visualization. For massive sulfide exploration, recognition and characterization of scattering anomalies in the unmigrated data volume is one of the key challenges for interpretation of the data. Recent published tests of this technique in South Africa and Canada indicate a promising outlook for 3-D seismics in mineral exploration, as the search for new ore deposits pushes to greater depths and the need for improved deep-imaging methods for surface exploration becomes increasingly important.

INTRODUCTION

Three-dimensional (3-D) seismic exploration is capable of providing the most complete subsurface picture of any surface-based geophysical technique. The essence of the method is areal deployment of sources and receivers on a 2-D grid, followed by processing and interpretation of the resulting densely sampled volumetric data. Under favourable conditions, 3-D seismic data provide the explorationist with a powerful tool for volume rendering and visualization of the subsurface. The inherent sensitivity to anomalous structures, spatial resolution and depth penetration capabilities of 3-D seismic surveys are all compatible with the requirements of deep (> 500 m) mineral exploration.

In oil and gas applications, 3-D seismic exploration is a mature technology that has profoundly influenced all aspects of exploration and development. First described in the literature 25 years ago (Walton, 1972), the method became commercially available through geophysical contractors in 1975 (Tegland, 1977) and underwent a period of explosive growth during the 1980s (Figure 1). In the latter part of 1996, 50 to 75% of worldwide seismic exploration activity comprised 3-D seismic surveys (Society of Exploration Geophysicists, 1996; 1997). The popularity of 3-D seismic methods for hydrocarbon exploration can be attributed to simple economics: its use has significantly reduced exploration costs by reducing the number of dry holes drilled (Greenlee *et al.*, 1994; Nestvold, 1996). In oil and gas exploration, most 3-D surveys are performed offshore, because the high cost of developing offshore fields warrants the additional delineation costs. This paper, however, will focus only on land 3-D seismic methods since these are most directly applicable to mining-related exploration.

The cost of 3-D seismic surveys is considerably higher than the cost of traditional geophysical methods used in mineral exploration. Furthermore, the technological risk of 3-D seismics in mining exploration is subject to considerable uncertainty. For example, the relationship of lithology to acoustic impedance, the rock property that primarily controls seismic response of the subsurface, is only starting to be understood for rock types relevant to mineral exploration (Salisbury *et al.*, 1996). In addition, the reflectivity characteristics of the crystalline crust differ in fundamental and important ways from reflectivity in sedimentary basins, impacting many aspects of seismic survey design (Milkereit

In "Proceedings of Exploration 97: Fourth Decennial International Conference on Mineral Exploration" *edited by* A.G. Gubins, 1997, p. 65–78

and Eaton, 1996). Without good borehole control, the interpretation of 3-D seismic data in crystalline terrains suffers from non-uniqueness (as do other geophysical techniques).

Few non-hydrocarbon 3-D seismic surveys have been recorded, and to date there exist only three published examples of full-scale 3-D seismic surveys focussed primarily on deep mineral exploration: the Oryx survey in the Witwatersrand Basin, South Africa (De Wet and Hall, 1994); the Trill survey in Sudbury, Canada (Milkereit *et al.*, this volume); and the Matagami survey, in the northern Abitibi subprovince of the Canadian shield (Adam *et al.*, this volume). These three surveys sample a diverse range of geological settings and mineral deposit types (gold, nickel and VMS, respectively). Taken together, they provide a preliminary basis for evaluating the potential of 3-D seismic technology for mineral exploration.

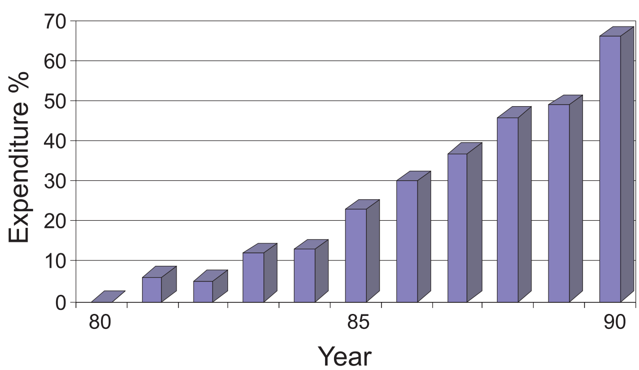


Figure 1: *Growth of 3-D seismic exploration in the oil and gas industry during the 1980s as reflected in 3-D seismic expenditures (as a percentage of total expenditures on seismic exploration) by Shell companies over the interval 1980 to 1990 (modified from Nestvold, 1992).*

As detailed case histories of these 3-D surveys are provided elsewhere, only the key results are summarized here. The objectives of this paper are: 1) to provide a brief tutorial on 3-D seismic techniques, aimed at the non-specialist; 2) to summarize important methodological differences between hydrocarbon and mining applications of 3-D seismics, drawing on the examples listed above; and 3) to describe cost-benefit trade-offs of 3-D seismic methods for mineral exploration in comparison with systematic drilling combined with downhole electromagnetics (EM). We begin by reviewing some fundamental aspects of seismics for mineral exploration, with particular emphasis on seismic prospecting in crystalline terranes.

SEISMIC PROSPECTING FOR ORE DEPOSITS

Seismic methods illuminate the subsurface using acoustic waves. The signals of interest arise from the reflection, refraction and scattering of waves at boundaries where abrupt changes in elastic properties occur. With the exception of coal exploration, seismic methods have had relatively limited use in mineral applications (Reed, 1993). This is due, in part, to the relatively high cost of seismic methods, coupled with a lack of detailed understanding of seismic velocities and densities of ores and host rocks. Recent results, however, indicate that seismic techniques can be effectively tailored for use in mining applications, although some modifications to standard practice are required in view of the complex scattering and weak reflectivity that characterizes seismic data from crystalline terranes (Milkereit *et al.*, 1996; Milkereit and Eaton, 1996).

Based on laboratory measurements at high confining pressure, Salisbury *et al.* (1996) recently reported the first comprehensive analysis of elastic properties of ores and host rocks. Salisbury *et al.* (1996) showed that: 1) pure sulphide and oxide minerals are characterized by acoustic impedance (the product of velocity and density) values that are systematically higher, by 10-60%, than felsic host rocks; and, 2) seismic velocities and densities of ore material composed of mixed sulphide minerals and host rocks are governed by simple linear mixing rules. These results provide a framework for understanding elastic properties of rocks in a mining setting, and the fundamental basis for the application of seismic methods for direct detection of ore deposits.

As well as a contrast in acoustic impedance of 10% or greater, several geometrical criteria must be met in order for an ore body, or any other geological feature, to be seismically visible. For example, a minimum layer thickness of ⅛ of the dominant seismic wavelength, λ, is required (Widess, 1973) to avoid cancellation of reflections of opposite polarity from the top and bottom. In addition, the full signal strength is observed only if the width of the anomalous zone is equal to, or greater than, the Fresnel diameter, given by $(2\lambda h)^{1/2}$, where h is depth (Sheriff and Geldart, 1995, p. 154). For a seismic velocity of 6000 m/s, a frequency of 50 Hz and a depth of 1 km, these criteria yield a minimum resolvable layer thickness of 15 m and a minimum width of 490 m for full scattering amplitude. Thus, seismic methods are limited in their sensitivity to the largest end members of ore deposits.

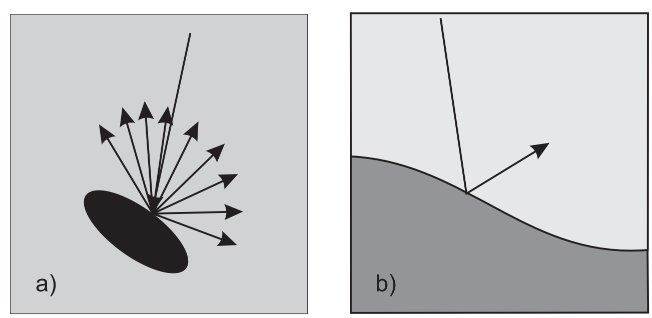


Figure 2: *(**a**) Scattering of an incident ray by a localized body, (**b**) compared with specular reflection of an incident ray by a continuous boundary.*

Processing and interpretation of seismic reflection data from sedimentary basins (either 2-D or 3-D) are based implicitly on an underlying layered-earth model. For example, seismic traces are organized and stacked to enhance continuous features; faults are often recognized based on vertical offsets of marker reflections; observed variations in amplitude are modelled assuming specular reflection from a quasi-planar boundary. In the crystalline crust, continuous marker reflections such as sills sometimes exist (e.g., Juhlin, 1990), but often do not. For successful application of seismic methods in crystalline terranes, it is paramount to consider scattering effects (Hurich, 1996), where scattering refers here to diffractions that originate from localized anomalous regions (Figure 2). These signals are considered to be of secondary importance to continuous reflections in conventional seismic processing and interpretation, but in the context of mining exploration they likely represent the most important component of the recorded seismogram. The preservation, enhancement and interpretation of scattered signals is a key difference between seismic applications for mining exploration, and traditional seismic applications in oil and gas work. Other important differences in the acquisition and processing of seismic data are noted by Milkereit and Eaton (1996).

WHY 3-D SEISMICS?

Although two-dimensional (2-D) seismic methods are logistically more straightforward and less expensive than 3-D methods, their imaging capabilities are inherently limited by the simplifying assumption that reflection (or scattering) points are limited to the vertical plane beneath the source-receiver line. Thus, conventional 2-D seismic methods are effectively limited to cases where: 1) structural elements have a long strike length compared with the depth of investigation, 2) the seismic profiles are oriented at a high angle to structural trends, and 3) exploration targets are large enough to avoid being overlooked in a network of widely spaced 2-D profiles.

In reality, geology is three-dimensional. Reflections from out of the plane, called *sideswipe*, are nearly always recorded and thus contaminate the 2-D image. Dramatic examples of sideswipe reflections and their imaging consequences are given by French (1974). 3-D seismic acquisition naturally eliminates these problems, since processing algorithms operate in three dimensions. In addition, 3-D seismic methods also provide tremendous benefit for interpretation due to the dense spatial sampling of the subsurface that is available. Features that might otherwise have been missed in a grid of 2-D seismic lines become apparent in a 3-D seismic survey.

Some of the arguments favouring the acquisition of 3-D seismic data are more compelling for mineral exploration in crystalline terranes than for hydrocarbon exploration in a sedimentary basin. The structural setting of ore deposits is most often one of polyphase deformation, in which the specification of a unique strike direction is meaningless. Hence, out-of-plane reflections are more likely to occur in a hard-rock setting than in a sedimentary basin. In addition, small, isolated scattering bodies (such as ore deposits) will have no preferred strike direction and, in principle, will be visible on profiles not located directly above them. This ambiguity is illustrated in Figure 3, which shows the modelled scattering response of a 45° dipping lens situated at a depth of 1800 m. Two profiles, one (line A) above the scattering body and another (line B) offset from it by 2 km. The scattering response of the dipping lens is visible on both line A and line B. After 2-D migration the anomaly is correctly positioned on line A, but has the wrong depth and apparent dip on line B. 2-D seismic profiles therefore contain, in general, scattered signals that originate from out of the plane of the section. These signals may be difficult, if not impossible, to distinguish from in-plane diffractions. On the other hand, scattered signals observed in 3-D seismic data can be located precisely. Figure 3 illustrates another important attribute of seismic scattering from small, dipping bodies: namely, that the peak scattered amplitude occurs in the down-dip direction. This observation implies that the acquisition array needs to be extended in the down-dip direction to ensure that the peak scattered energy is recorded. For lenses with complex shape, the preferential direction of reflected seismic energy is difficult to predict and requires forward modelling.

FUNDAMENTALS OF 3-D SEISMIC EXPLORATION

Data acquisition

3-D seismic data are acquired by deploying sources and receivers on a 2-D surface grid, for which several grid layouts are commonly used. Figure 4 shows schematic representations of acquisition grids used for the three published mining 3-D surveys. In the South African Oryx survey, source lines formed a zig-zag pattern between parallel receiver line, a pattern referred to as *forced-centre* traversing. This configuration is most useful when a narrow strip of receivers is used for each source, but fails to provide azimuthal subsurface coverage that is as complete as the other grid designs. The Trill 3-D survey was acquired using irregular source lines oriented roughly perpendicular to a series of straight, parallel receiver lines. This approach was used in order to mitigate the environmental impact of constructing access trails for off-road vehicles needed to drill shotholes. The Matagami 3-D survey was acquired using a perpendicular set of source and receiver lines, a configuration that is the most commonly used in hydrocarbon exploration. This grid design minimizes acquisition and surveying difficulties, but tends to introduce directional bias along the directions of the grid axes. For both the Matagami and Sudbury surveys, the grids were aligned with the dominant strike direction.

Dynamite and vibroseis are the two most common sources used for land 3-D seismic surveys (Sheriff and Geldart, 1995). In the case of the Oryx survey, shotholes were only drilled in areas of difficult access. Elsewhere, vibroseis units were used to provide a seismic source. Both the Trill and Matagami 3-D surveys used small dynamite charges placed in shotholes. Because of extensive outcrop exposure, many of the shotholes for the Trill survey were drilled directly into bedrock, providing an extremely consistent source containing higher frequencies than shots drilled into overburden or surface shots (Milkereit *et al.,* this volume). The Matagami area is flat, low-lying and generally devoid of outcrop. Here, shotholes were drilled into a thick layer of glacial till (Adam *et al.*, this volume).

In general, the acquisition grid needs to be larger than the surface projection of the target zone for several reasons: 1) to ensure that the target area lies within the region of maximum subsurface coverage (see Milkereit *et al.*, this volume); and, 2) to account for the down-dip focussing of scattered wave energy (Figure 3). As a general rule, the acquisition grid should extend from the target zone into the down-dip direction at least as far as the depth of investigation.

Data processing

The basic 3-D processing sequence consists of a series of steps that include: 1) amplitude scaling; 2) deconvolution; 3) first-break picking and muting; 4) refraction statics corrections; 5) sorting traces into common midpoint (CMP) bins; 6) normal moveout correction; 7) dip-moveout correction; 8) stack; 9) 3-D migration. For a complete description of these steps, the reader is referred to Yilmaz (1987) and Sheriff and Geldart (1995). Several key steps deserve particular attention, however. For example, in glaciated crystalline terranes, a low-velocity overburden layer directly overlies high-velocity bedrock. Variations in the thickness of the overburden, coupled with the unusually large velocity contrast at the bedrock interface, produce highly problematic time shifts that cause misalignment of scattered seismic signals. Thus, step (4) in the above

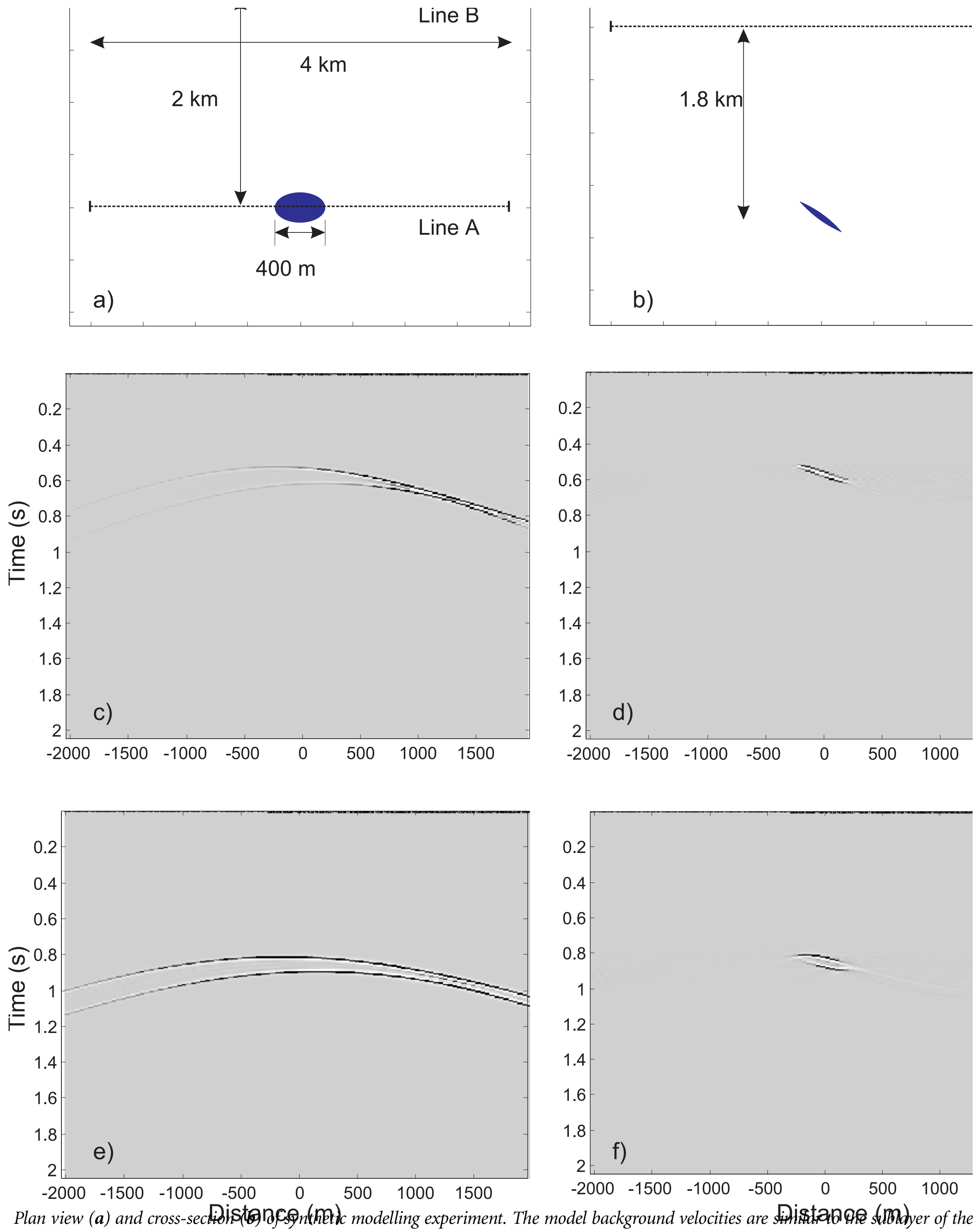


Figure 3: *Plan view (**a**) and cross-section (**b**) of synthetic modelling experiment. The model background velocities are similar to the sublayer of the Sudbury Igneous Complex, having a P-wave velocity of 6300 m/s, S-wave velocity of 3200 m/s and a density of 2.75 g/cm³. The 45° dipping lens is modelled to have a composition similar to nickel ores in Sudbury, with a 10% lower P-wave velocity, a 5% higher S-wave velocity and 50% higher density than the surrounding rocks. Unmigrated (**c**) and migrated (**d**) scattering response of the dipping lens, recorded by a profile directly above the lens (line A). Note focus-sing of amplitudes in the down-plunge direction. Unmigrated (**e**) and migrated (**f**) response for line B, located 2 km off the dipping lens.*

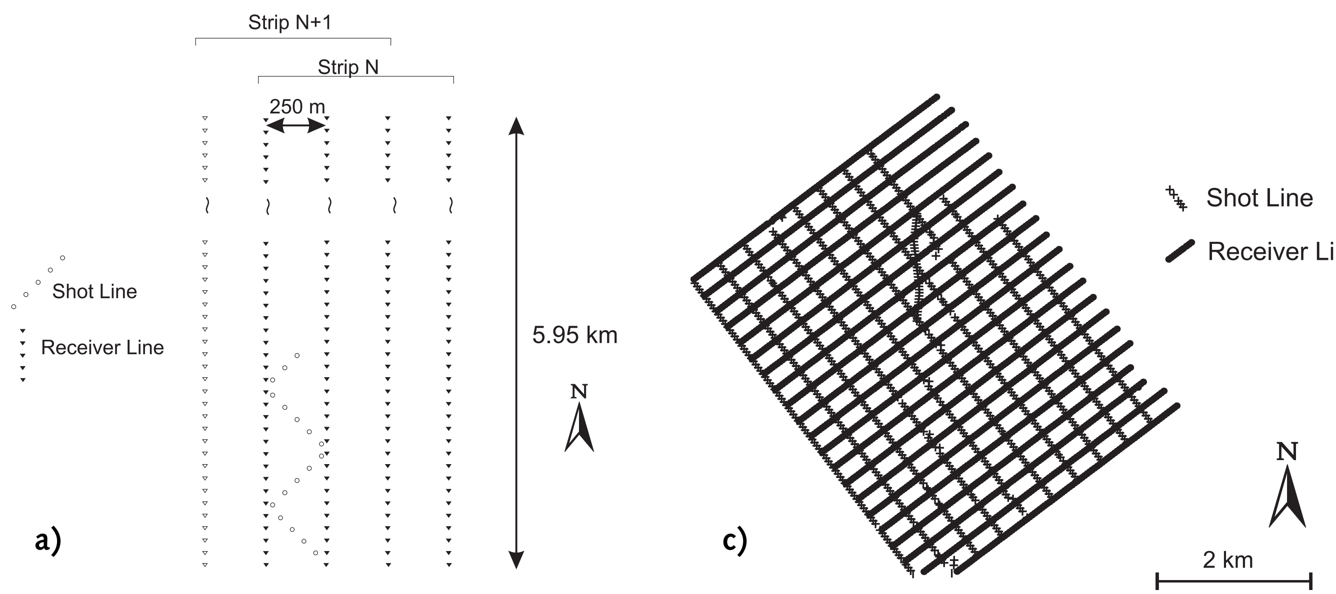
sequence (refraction statics corrections) often requires special care. In addition, noise is often well separated from signal in the frequency domain (Milkereit and Eaton, 1996), and simple, robust approaches to deconvolution, such as spectral balancing, have proven to be effective.

Certain processing steps focus reflections and scattered signals into a coherent image in a manner that depends on the velocity model used. Included in these imaging steps are *dip moveout* and *migration*. Dip moveout is applied before stacking, and is necessary for the preservation of steeply dipping reflections and diffractions (Adam *et al.*, this volume). Typically, the final step in 3-D seismic processing is post-stack migration, which collapses diffractions into a point and re-positions dipping reflections into their correct subsurface position. The crystalline crust introduces two important benefits for these imaging procedures: 1) because of the relatively homogeneous velocity field of about 6000 m/s, estimation of the velocity model is greatly simplified; 2) uniform rock velocities allow easy conversion of two-way reflection time to approximate depth (i.e., a reflection at 1 s two-way time originates from a depth of ~3000 m).

Interpretation

After processing, the 3-D data are arranged into a format referred to as a *data cube* (although the dimensions of each axis of the cube are in general not equal) which provides organized access to the volumetric information. Although the full potential of 3-D seismic data can be realized using 3-D visualization tools, it is often simpler to perform the interpretation using 2-D sections taken through the cube (Figure 5). *Inline* and *crossline* 2-D sections are similar in appearance to conventional 2-D seismic profiles, but have superior resolution due to 3-D processing used in their construction. Arbitrary 2-D vertical sections through the 3-D volume, not necessarily aligned with inline or crossline directions, are also possible. *Time slices*, in which data from a specific time (or time window) are displayed for all CMP bins, yield approximately horizontal sections through the data cube.

Some of the benefits of interpretation using the conventional time slice approach are illustrated in Figure 6, which shows a time slice at 2.168 s, from a migrated 3-D data set from Alberta, Canada (Isaac and



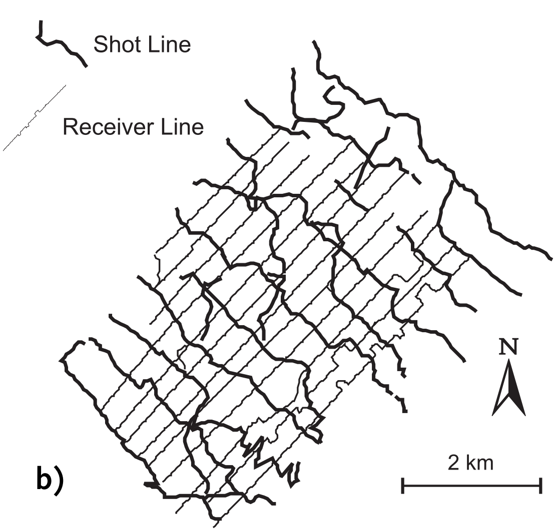


Figure 4: *Source-receiver configurations used for:*

*(**a**) the Oryx 3-D survey (De Wet and Hall, 1994),*
*(**b**) the Trill 3-D survey (Milkereit et al., this volume), and*
c) the Matagami 3-D survey (Adam et al., this volume).

Stewart, 1993). This time slice contains a dramatic sub-circular anomaly that has been attributed to a meteorite impact structure formed in Late Cambrian to Middle Devonian time (Isaac and Stewart, 1993). Without this 3-D seismic information, the diagnostic circular shape of this feature would not have been evident and the meteorite interpretation might not have been realized.

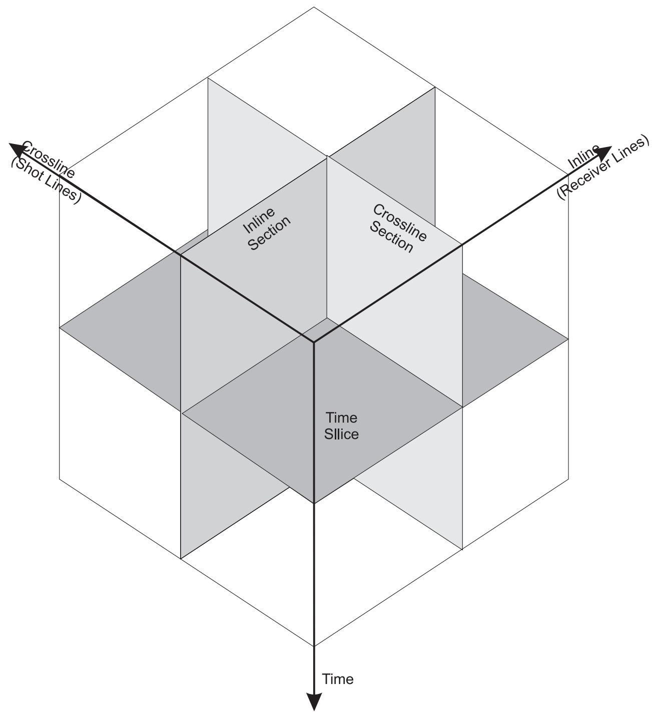


Figure 5: *Index to terms used in the section-based interpretation of 3-D seismic data.*

As in the previous example, migrated sections form the basis for interpreting conventional 3-D seismic surveys in sedimentary basins, since after migration dipping reflections are positioned correctly in the subsurface. However, unmigrated 3-D seismic data provide a useful tool for recognizing and interpreting scattering anomalies caused by localized features, such as ore deposits, and so may play a more important role in mineral exploration than is the case for oil and gas work. Figure 7 shows time slices through unmigrated synthetic data computed using the Born approximation (Eaton, 1997) based on a 3-D subsurface model for part of the Sudbury Basin constrained by drilling information. The model contains a small, high-density scattering body, representing the Creighton 402 ore body, and a reflector (FC) which represents the footwall contact between the Sudbury Igneous Complex and the underlying Levack Gneiss. The modelled seismic response of the ore deposit (402) is indicated by concentric rings of expanding radius with increasing time, whereas the reflecting boundary is represented as a prominent quasi-linear feature. The centre of curvature of the 402 scattering feature is the same in every time slice, whereas the FC reflection moves slightly from one time slice to the next. These features allow scattering anomalies to be distinguished from reflections using unmigrated 3-D seismic data.

After migration, the scattering anomaly becomes focussed to a small point that might easily be overlooked when interpreting the data.

If a circular ring-shaped feature, such as described above for the modelled response of the Creighton 402 ore body, is observed in an unmigrated time slice, the x-y position of the corresponding scattering body can be determined easily by taking its centre of curvature. The depth, z, of the causative body can be computed using :

$$z = \frac{v}{2}\sqrt{t^2 - \frac{d^2}{v^2}} \qquad [1]$$

where v is the velocity, t is time and d is diameter of the circular anomaly.

EXAMPLES

Oryx 3-D survey

The Oryx 3-D survey was acquired by Gengold Mine Management and Consulting in 1991. A case history and description of this survey is given by De Wet and Hall (1994). The 42.25 km^2 was acquired over the Beisa Mine in the Witwatersrand Basin, South Africa using both vibroseis and dynamite sources. Unlike the other two 3-D surveys considered here, this survey was conducted for mine planning purposes, rather than for exploration. The objective was to map the Kalkoenkrans Reef, the gold producing horizon in this mine. Since this horizon is only 6 m (or less) in thickness, it falls below the resolution limits of seismic methods. Therefore the project attempted to infer the reef geometry by mapping conformable structures surrounding the Kalkoenkrans Reef itself.

The survey used 480 channel acquisition and relied primarily on vibroseis sources, reserving dynamite shots for areas inaccessible to the vibroseis units. Using sweep frequencies of 10–90 Hz, the survey was successful in obtaining an image of the folded base of the Eldorado Formation, which is generally conformable with the target horizon. Observed dips were lower than expected, necessitating some changes in mine plans to account for this. Although 64 boreholes were used in the interpretation, significant uncertainties in time-to-depth conversion were caused by the lack of velocity logging.

Trill 3-D survey

The Trill 3-D seismic survey (Milkereit *et al.*, this volume) was acquired at the west end of the Sudbury Basin, the richest Ni-producing region in the world. Nickel deposits occur as pyrrhotite-rich massive sulfide bodies within the Sudbury Igneous Complex, a differentiated sequence of gabbro, norite and granophyre thought to be the magmatic record of a large impact event (Boerner *et al.*, 1994). Although ores can be profitably mined in Sudbury to depths of 2.5 km, current surface-based geophysical techniques are limited to depths of about 500 m, providing a strong motivation to develop new technology for deep mineral exploration (Milkereit *et al.*, 1996).

The Trill 3-D seismic survey was acquired in October 1995 atop an unmined mineralization zone at 1800-m depth that had been previously delineated by drilling and magnetotelluric investigations (Livelybrooks *et al.*, 1996). The location and design of the survey were the subject of an extensive site-selection process (Milkereit *et al.*, this volume). The objectives of the survey were: 1) to image the geometry of the igneous sublayer, which hosts nickel deposits in the Sudbury Basin; 2) to characterize the

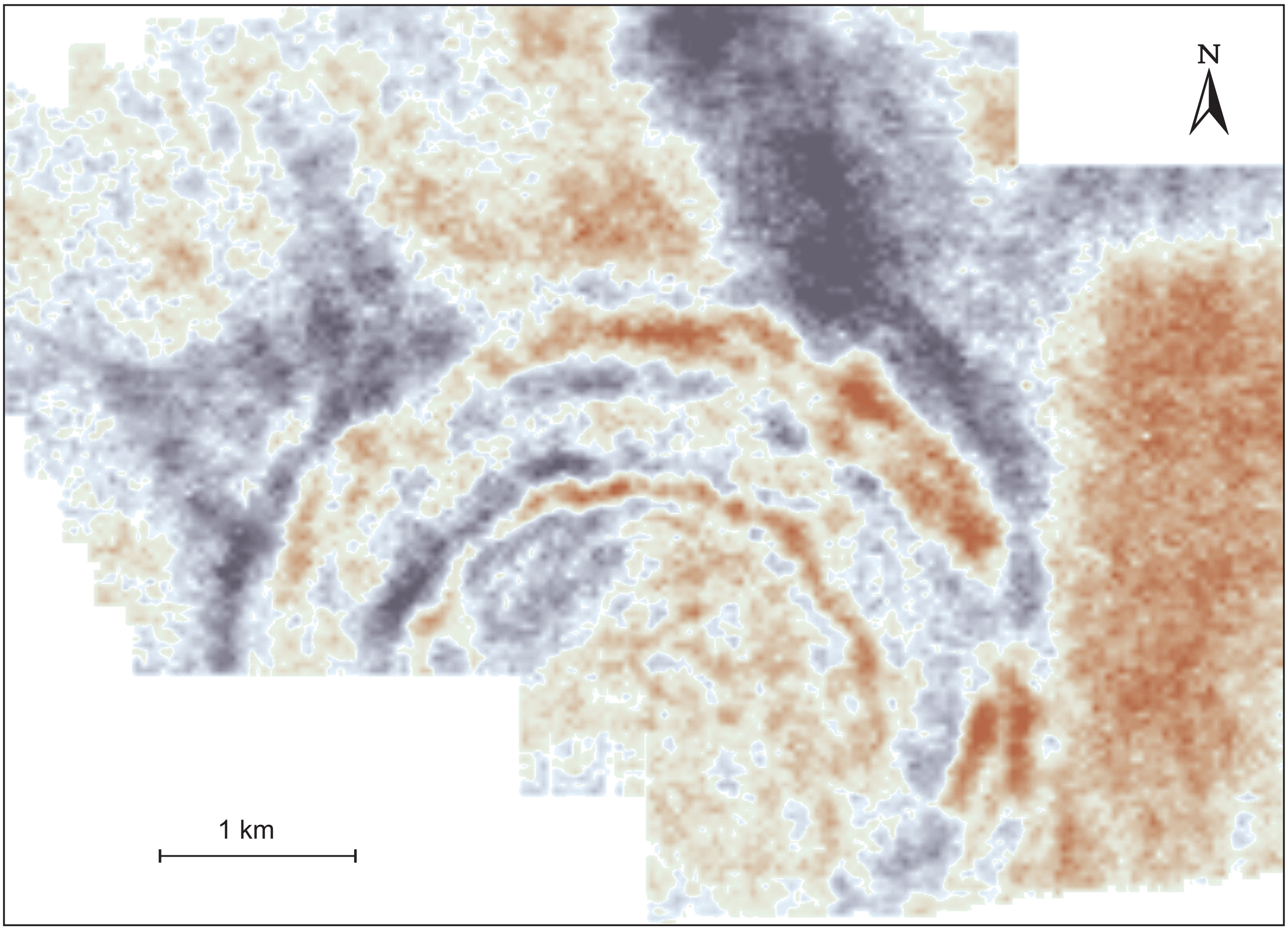


Figure 6: *Time slice from the James River 3-D seismic survey in Alberta, Canada, showing the circular plan of the beds diagnostic of an impact structure*

3-D seismic response of the Trillabelle massive sulfide body, and 3) to combine physical-rock property, seismic and drill-hole information in an integrated interpretation.

Figure 8 shows a time slice at 642 ms (approximately 2000 m depth) through the unmigrated 3-D data volume. The data have been interpreted using an interactive workstation, allowing observed seismic events to be picked throughout the data cube and integrated with other information. Figure 8 shows picks (small diamonds) that outline a prominent scattering anomaly interpreted to originate from the Trillabelle deposit. Using equation (1), the depth of origin for the anomaly is in good agreement with the known mineralization, but the massive sulphide deposit does not coincide exactly with the centre of curvature of the observed scattering anomaly. This discrepancy may be due to waveform interference effects (Milkereit *et al.*, this volume), or the available subsurface control from drilling may not be sufficient to outline entirely the mineralized zone (B. Roberts, pers. comm., 1997).

In addition to the possibility of direct detection of mineralized zones, 3-D seismic data also provide a tool for mapping local structure. In Sudbury, rock property data indicate that the top of the sublayer (a mass of mafic and ultramafic inclusions in a matrix of norite and sulfides) and its base (the footwall contact) are characterized by significant acoustic impedance contrasts, and thus both should represent observable seismic reflectors. The geometry of the sublayer on cross-line 220, projected from available drilling information, is conformable with reflections where the dips are shallow or moderate (Figure 9). Based on this correlation, the sublayer geometry and thickness have been systematically mapped by tracing these reflections through the migrated 3-D data cube, outlining an embayment feature (Milkereit *et al.*, this volume). Structural elements such as this embayment are important for mineral exploration, as they represent favourable settings for economic mineral occurrences.

Matagami 3-D survey

The 20 km^2 Matagami 3-D survey was acquired in April 1996 by Noranda Mining and Exploration Ltd. The objectives of the 3-D survey were (Adam *et al.*, this volume): 1) to determine the seismic expression of the Bell Allard ore body, a 6-million-tonne Zn-Cu deposit, and, 2) to attempt to define other, similar features within the 3-D data volume, using the Bell Allard seismic response as a template. The survey also provides a tool for mapping the Key Tuffite horizon in three dimensions.

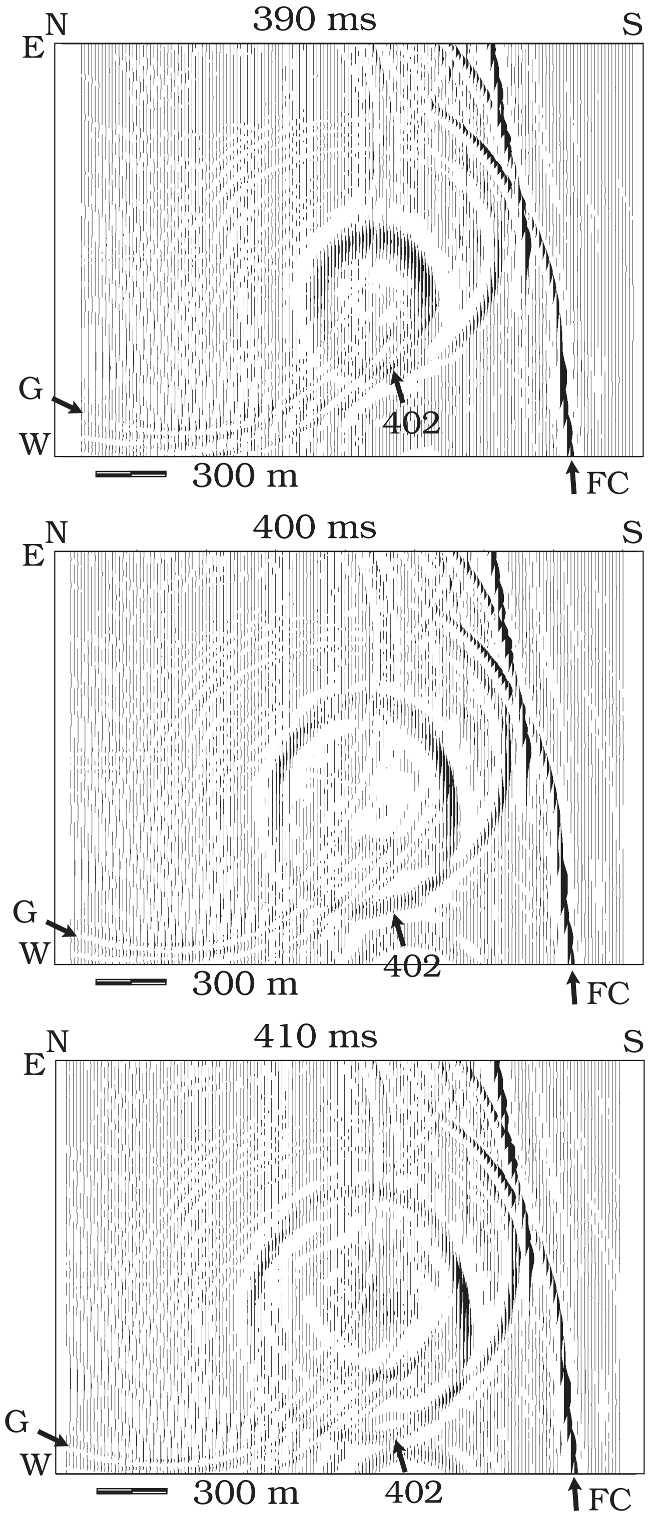


Figure 7: *Series of time slices at 390, 400 and 410 ms from a synthetic modelling study of the Creighton 402 ore body in the Sudbury Basin. FC = Footwall Contact, G = Gertrude ore body, 402 = Creighton 402 ore body (after Milkereit and Eaton, 1996).*

The Key Tuffite occurs along the contact between the Lower Wabassee and Watson Lake Groups, and is spatially and stratigraphically associated with mineralization in the area. The study area, situated on the south flank of the Galinée anticline in the Matagami mining camp, has been the site of extensive 2-D seismic testing and borehole geophysical logging since 1990. The results of these tests showed that this area is well suited for the application of seismic techniques for exploration, since large impedance contrasts occur in association with lithologic contacts and ore deposits, and structural dips are moderate (Milkereit *et al.*, 1991; Adam *et al.*, 1996). Details of the acquisition, processing and interpretation of this survey are given by Adam *et al.* (this volume).

The presence of a low-velocity glacial till layer of highly variable thickness above high-velocity tholeiitic volcanic rocks presented significant challenges for processing these data. Figure 10a shows the weathering model obtained by refraction statics analysis. Note that pockets of overburden attain a thickness of more than 50 m. The statics solution that corresponds with this weathering model is shown in Figure 10b. Statics of more than 100 ms were needed to correct for time delays in the thick overburden. Note that without accurate statics corrections, no useful reflection images could be obtained from this survey.

Figure 11 shows a migrated depth slice at 800 m, illustrating the mapping capabilities of the 3-D seismic data. Continuous northwest striking reflections west of the Key Tuffite horizon represent alternating felsic-mafic volcanic units within the Lower Wabassee group. To the east, the zone of mainly chaotic reflectivity falls within the Watson Lake group. Isolated reflections within the Watson Lake originate from gabbroic intrusions, some of which crosscut the Key Tuffite horizon. Ore deposits in the Matagami camp occur at the Key Tuffite, which marks a hiatus in volcanic activity.

COST-BENEFIT ANALYSIS

To evaluate the utility of 3-D seismic exploration for mining applications, its potential benefits must be weighed against the relatively high costs of this technique. Prior to the acquisition of the Oryx 3-D survey, a cost-benefit study of 3-D seismics for gold mine planning in South Africa was undertaken by Gencor (DeWet and Hall, 1994). Gencor determined that the method is cost effective if the target depth exceeds 1000 m. For gold mines at depths of more than a kilometre, structural information obtained from 3-D seismic interpretation can be used to bring the mine to profitability more quickly and at a lower cost than delineating the prospect by drilling alone (De Wet and Hall, 1994).

Adam *et al.* (this volume) estimate a cost of $50,000 (Canadian dollars) per km^2 for a 3-D seismic survey covering 20 km^2 in the Canadian Shield. From the results of the Matagami 3-D survey, Adam *et al.* (this volume) concluded that 3-D seismics are appropriate only as a method of sterilizing a prospect area for depths >500 m, since at shallower depths the data quality for 3-D seismic surveys is generally poor. Since the core area of a 3-D survey is roughly 50% smaller than the area of the acquisition grid, an effective cost of $100,000 per km^2 is probably more realistic. To put these costs into perspective, the average cost of finding an economic mineral deposit in the Canadian Shield has been estimated as $32.5 million (Mackenzie, 1989), based on an assumed 2% likelihood that a mineral occurrence proves economic. Under the assumption that no more than 25% of the finding cost is available for seismic expenditures, economic considerations dictate an upper bound of 81 km^2 of

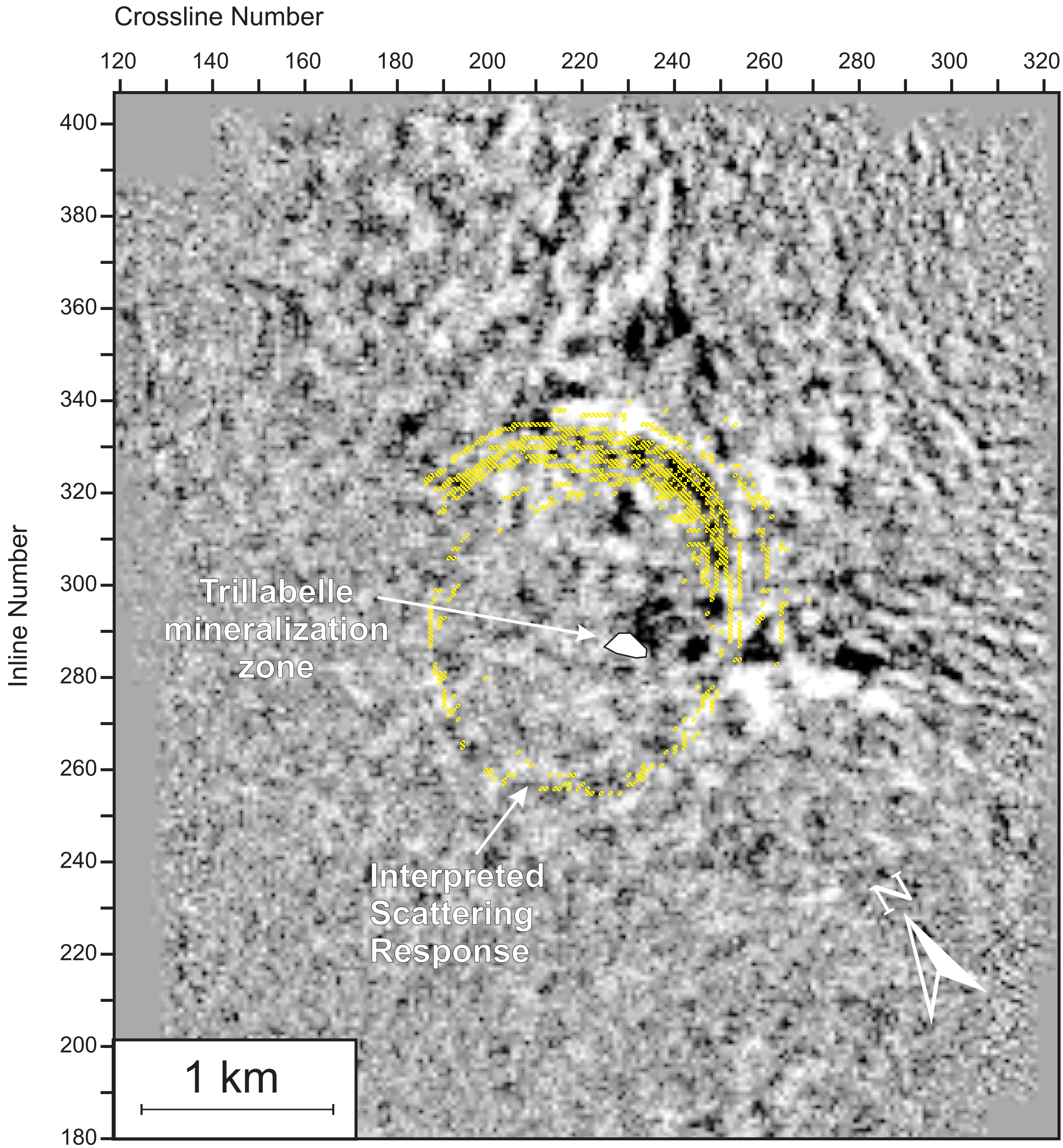


Figure 8: *Time slice from the Trill 3-D seismic survey at 642 ms (~2 km depth), showing interpreted sub-circular response of the Trillabelle mineralization zone in the unmigrated seismic data.*

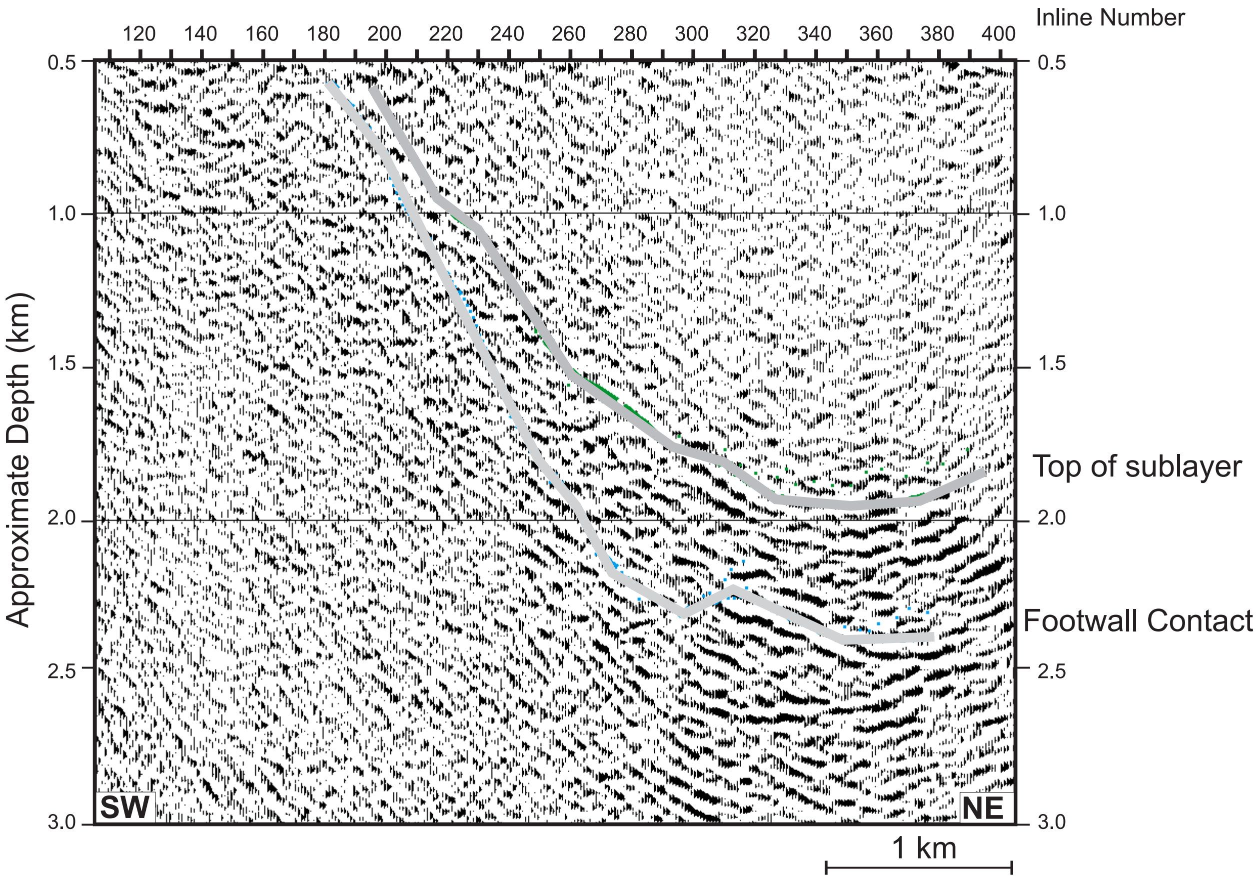


Figure 9: *Cross-line 219 from the depth-migrated Trill 3-D survey, showing partly continuous reflections from the top of the sublayer, and from the footwall contact. Interpretations shown are based on drilling control. Note that the opposite naming convention for crosslines and inlines has been used for this survey, and that this profile extends farther southwest than the southwestern limit of the time slice in Figure 8.*

areal coverage for each economic mineral occurrence in order for 3-D seismic exploration to be considered cost effective. This represents about four surveys of the magnitude of the Matagami or Sudbury experiments.

Systematic drilling coupled with downhole EM surveys represent a currently favoured method for sterilizing a prospect area in base-metal exploration (Williams, 1996). Downhole EM techniques are now routinely used to test for large conductive bodies up to 300 m from the drill hole (King *et al.*, 1996), implying that a borehole spacing of 600 m is sufficient for an exhaustive search. However, for our present purposes, we assume that one borehole per km^2 is sufficient for deep exploration, since only large deposits can be mined economically at depths of more than 500 m. Based on this assumption, and assuming that ore deposits are distributed in a spatially random manner, then 3-D seismic methods become cost effective once the average cost of drilling to the maximum exploration depth, as well as costs incurred for EM soundings, exceeds \$100,000. Assuming drilling costs in the range of \$80–100 per metre (Williams, 1996), this represents a crossover target depth of approximately 1000–1250 m, below which 3-D seismics are less expensive than the alternative approach of systematic drilling and EM. If ore deposits can be constrained, using other information, to fall within a trend which is narrower than a few kilometres (the minimum practical width for a 3-D acquisition grid), then the crossover depth becomes correspondingly deeper.

In weighing the various pros and cons, the foregoing discussion omits several points that are pertinent for evaluating the *technological risk*. First, in the present state of knowledge the seismic signatures of massive sulfide deposits are not as well understood as their EM signatures. Whereas the EM response depends on an intrinsic property (conductivity), the reflectivity of an ore body depends on the properties of both the ore minerals and the host rocks, as well as the shape and attitude of the deposit (Salisbury *et al.*, 1996). Both seismic and EM methods may be prone to spurious anomalies such as conductive graphite zones (in the case of EM methods) or small intrusive bodies (in the case of seismic methods). However, seismic methods have the distinct advantage that they may also provide valuable information about the geological setting and structural context of an interpreted anomaly.

Significant reductions in the cost of 3-D seismic methods for mineral exploration might also be possible, but further work is required. Parameters necessary to achieve acceptable 3-D seismic data quality in sedimentary basins, such as the minimum fold and offset range, are usually well established. In crystalline terranes, only best guesses are possible. Since the cost of 3-D surveys depends almost linearly on the number of source points used (Sheriff and Geldart, 1995), any reduction in the spatial density of sources will inevitably produce savings. Revised processing and interpretation methods focussed on scattering analysis, rather then conventional CMP stacking, are particularly promising avenues of research that could lead to more sparse approaches for data acquisition.

CONCLUSIONS

To date, results from three 3-D seismic surveys for mine planning or mineral exploration purposes have been published: Witwatersrand Basin, South Africa; Sudbury, Canada; and, Matagami, Canada. The flexibility of the method is reflected by its successful application in a diverse range of geological settings, including sediment-hosted gold deposits, igneous nickel and volcanogenic massive sulfides. In the Witwatersrand Basin, the Oryx 3-D survey was used to map the Kalkoenkrans Reef, showing that its dip was not as steep as expected. The Trill 3-D survey in Sudbury contains distinct, mappable reflections from the top and base of the sublayer of the Sudbury Igneous Complex, useful for delineating embayment structures that provide favourable settings for nickel occurrences. The unmigrated 3-D data also contain a prominent scattering anomaly which is interpreted to be the seismic expression of the Trillabelle massive sulfide deposit. The Matagami 3-D seismic survey shows reflections from the Lower Wabassee Group that are conformable with the Key Tuffite, the main target horizon for Zn-Cu exploration.

3-D seismic exploration is most appropriate for mature mining camps where extensive borehole control exists and a good geological

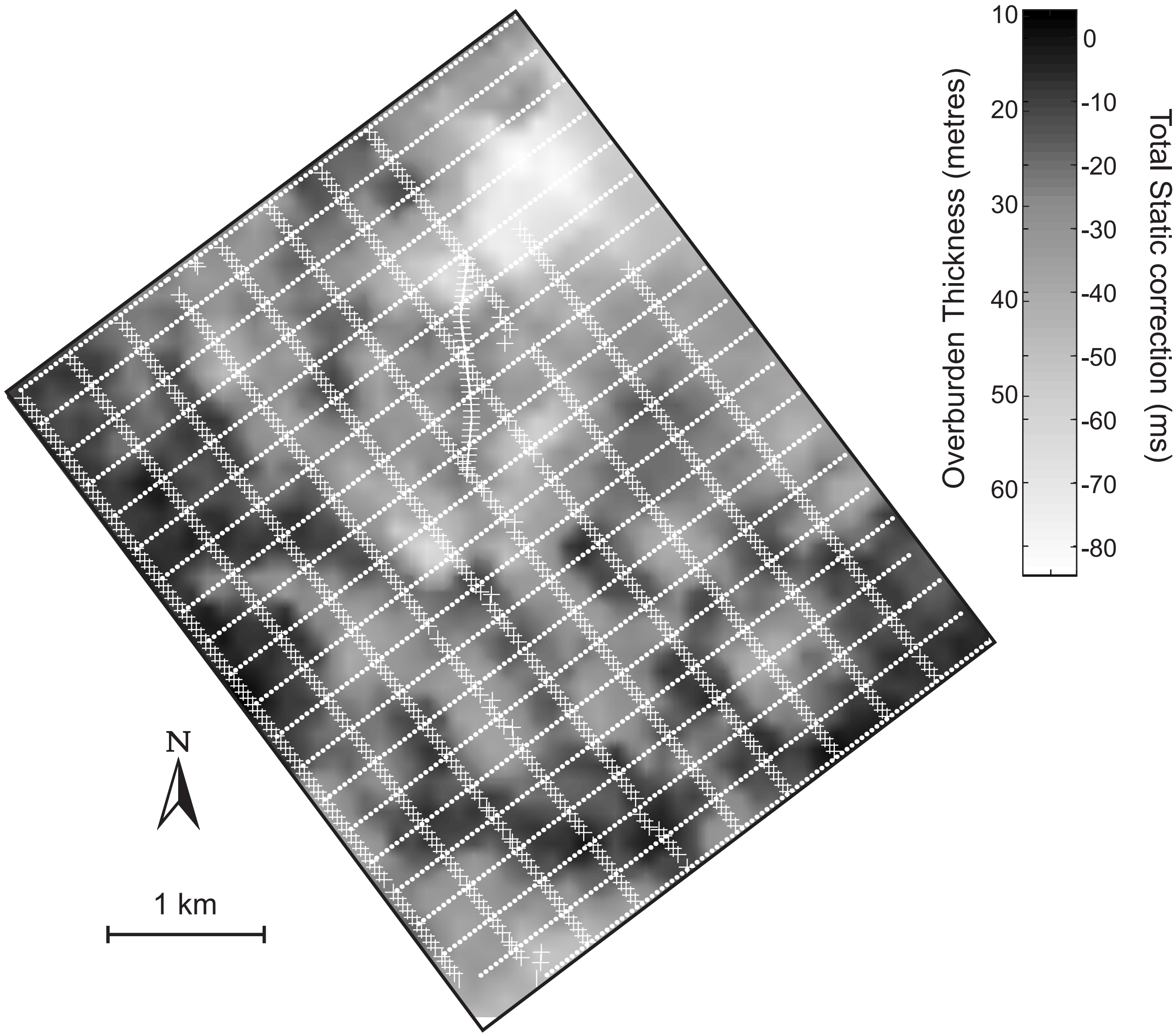


Figure 10: *Overburden thickness model and statics corrections determined by 3-D refraction statics analysis of first-break time picks for the Matagami 3-D seismic survey, showing the locations of source (crosses) and receivers (dots). Note extremely thick (> 50 m) pocket of low-velocity overburden at the north corner of the survey grid, necessitating static corrections more than 80 ms in magnitude.*

model is available. The method is relatively expensive, but cost-benefit analysis suggests that, for both mine planning and base-metal exploration, the method is cost-effective for target depths greater than about 1 km. Reducing the number of required source positions, possibly by introducing scattering-oriented processing and analysis techniques, could lead to reductions in the cost of data acquisition.

ACKNOWLEDGEMENTS

The seismic data from Canada were acquired by Solid State Geophysics (Trill survey) and Enertec (Matagami survey). The Trill and Matagami 3-D seismic surveys were conducted, in part, under the Industry Partners Program of the Geological Survey of Canada. We are grateful to

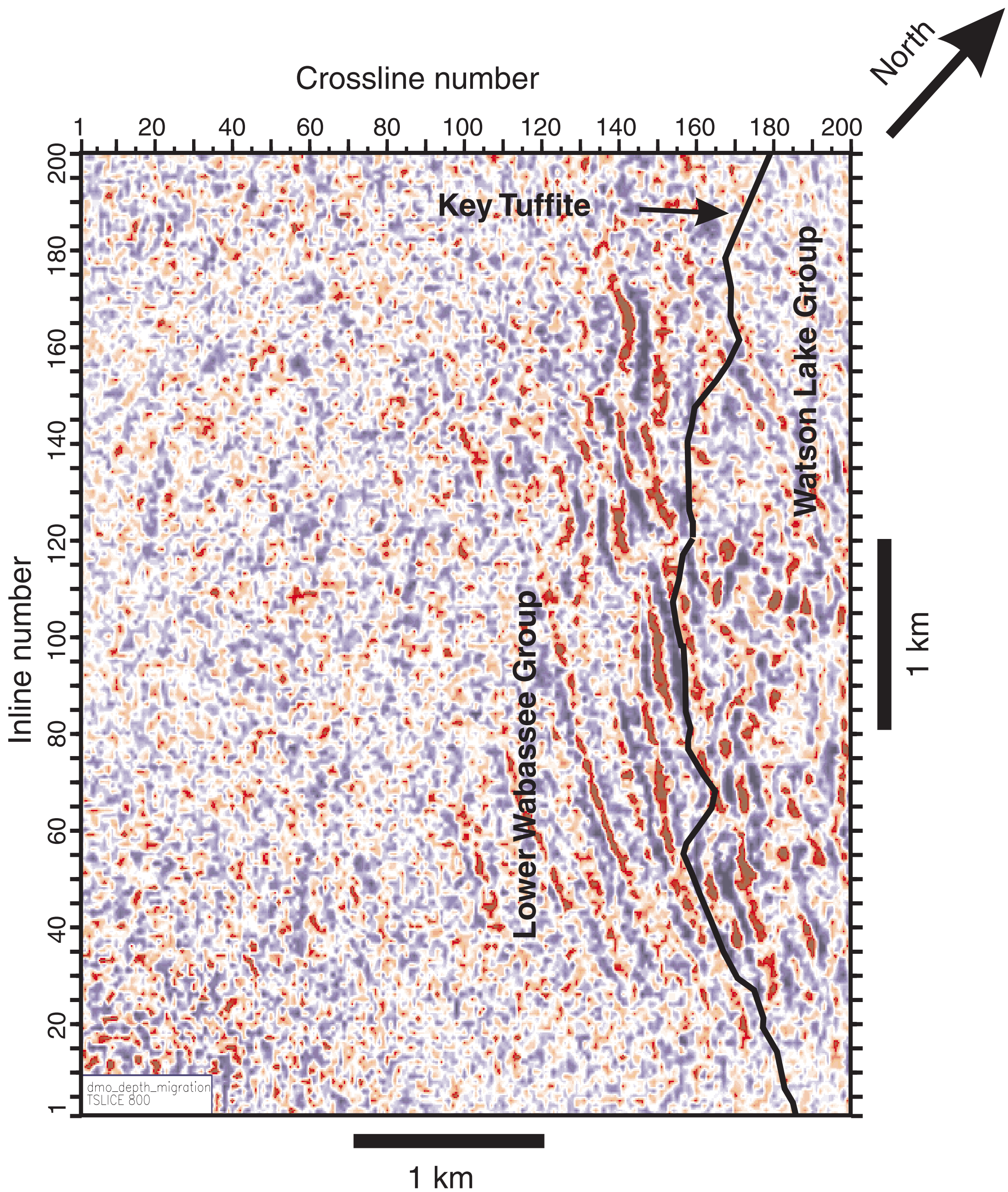


Figure 11: *Migrated depth slice at 800 m from the Matagami 3-D survey. Note difference in seismic expression of layered volcanics of the Lower Wabassee Group, west of the Key Tuffite, compared with the reflectivity pattern of the Watson Lake Group. Data showing the seismic expression of the Bell Allard ore body are not released for publication at the time of writing.*

Falconbridge, Ltd., Inco, Ltd. and Noranda Mining and Exploration, Ltd., for permission to publish this work. Jianjun Wu, Brian Roberts, Gervais Perron, Larry Matthews and Matthew Salisbury all made significant contributions to various stages of the Trill and Matagami 3-D seismic projects. This paper is GSC contribution number 1996500.

REFERENCES

Adam, E., Arnold, G., Beaudry, C., Matthews, L., Milkereit, B., Perron, G., and Pineault, R., this volume, Seismic exploration for VMS deposits, Matagami, Québec.

Adam, E., Milkereit, B., Arnold, G., and Pineault, R., 1996, Seismic response of the Bell Allard orebody, Matagami, Québec: 66th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 634-637.

Boerner, D.E., Milkereit, B., and Naldrett, A.J., 1994, Introduction to the Special Section on the Lithoprobe Sudbury Project: Geophysical Research Letters, 21, 1-4.

Brown, A.R., 1991. Interpretation of three-dimensional seismic data, third edition. AAPG Memoir 42, AAPG, Tulsa, 341 pp.

De Wet, J.A.J., and Hall, D.A., 1994, Interpretation of the Oryx 3-D seismic survey: South Africa Institute of Mining and Metallurgy, **3**, 259-270.

Eaton, D.W.S., 1997, BMOD3D: A program for threedimensional seismic modelling using the Born Approximation: Geological Survey of Canada, Open File 3357, 26 pp.

French, W.S., 1974, Twodimensional and threedimensional migration of model-experiment reflection profiles. Geophysics, **39**, 265-277.

Greenlee, S.M., Gaskins, G.M., and Johnson, M.G., 1994, 3-D seismic benefits from exploration through development: An Exxon perspective: The Leading Edge, **13**, no. 7, 730-734.

Hurich, C.A., 1996, Statistical description of seismic reflection wavefields: A step towards quantitative interpretation of deep seismic reflection profiles: Geophys. J. Int., **125**, 719-728.

Isaac, J.H., and Stewart, R.R., 1993, 3-D seismic expression of a cryptoexplosion structure: Can. J. Expl., Geophys., **29**, 429-439.

Juhlin, C., 1990, Interpretation of the reflections in the Siljan Ring area based on results from the Gravberg-1 borehole: Tectonophysics, **173**, 345-360.

King, A., Fullagar, P., and Lamontagne, Y., 1996, Borehole geophysics in exploration, development and production, *in* Lawton, S.E., ed., Trends, Technologies and case histories for the modern explorationist: Prospectors and Developers Association, Short Course Proceedings, 239-275.

Livelybrooks, D., Mareschal, M., Blais, E., and Smith, J.T., 1996, Magnetotelluric delineation of the Trillabelle massive sulfide body in Sudbury, Ontario: Geophysics, **61**, 971-986.

Mackenzie, B.W., 1989, Mineral exploration economics: Focusing to encourage success, *in* G.D. Garland, ed., Proceedings of Exploration '87,: Third Decennial International Conference on Geophysical and Geochemical Exploration for Minerals and Groundwater: Ontario Geological Survey, Spec. Vol. 3, 3-21.

Milkereit B., Berrer, E.K., Watts, A., and Roberts, B., this volume, Development of 3-D seismic exploration technology for Ni-Cu deposits, Sudbury Basin.

Milkereit, B., and Eaton, D.W., 1996, Towards 3-D seismic exploration technology for the crystalline crust, *in* S.E. Lawton, ed., Trends, Technologies, and Case Histories for the Modern Explorationist: Prospectors and Developers Association of Canada, Short Course notes, 17-36.

Milkereit, B., Adam, E., Barnes, A., Beaudry, C., Pineault, R., and CinqMars, A., 1991, An application of reflection seismology to mineral exploration in the Matagami area, Abitibi belt, Québec, *in* Current Research, Part C: Geological Survey of Canada, Paper 92-1C, 13-18.

Milkereit, B., Eaton, D., Wu, J., Perron, G., Salisbury, M., Berrer, E., Morrison, G., 1996, Seismic imaging of massive sulphide deposits, part II: Reflection seismic profiling: Economic Geology, **91**, 839-844

Nestvold, E.O., 1992, 3-D seismic: Is the promise fulfilled? The Leading Edge, **11**, no. 6, 12-19.

Nestvold, E.O., 1996, The impact of 3-D seismic data on exploration, field development, and production, *in* P. Weimer and T.L. Davis, eds., Three-Dimensional Seismic Methods: AAPG Studies in Geology No. 42 and SEG Geophysical Developments Series No. 5, 1-8.

Reed, L.E., 1993, Seismic reflection surveying for mining exploration applications: A review of practice past and current with an outlook for the future: Mineral Industry Technology Council of Canada, unpublished report, 219 pp.

Salisbury, M.H., Milkereit, B., and Bleeker, W., 1996, Seismic imaging of massive sulfide deposits, part I: Rock properties: Economic Geology, **91**, 821-828.

Sheriff, R.E., and Geldart, L.P., 1995, Exploration Seismology, Second Edition: Cambridge University Press.

Society of Exploration Geophysicists, 1996, SEG Seismic Activity Survey: The Leading Edge, **15**, no. 12, 1407-1408.

Society of Exploration Geophysicists, 1997, SEG Seismic Activity Survey: The Leading Edge, **16**, no. 1, 77-78.

Tegland, E.R., 1977, 3-D seismic techniques boost field development: Oil and Gas Journal, **75**, no. 37, p. 79-82.

Walton, G., 1972, Three-dimensional seismic method: Geophysics, **37**, 417-430.

Widess, M.B., 1973, How thin is a thin bed? Geophysics, **38**, 1176-80.

Williams, P., 1996, Using geophysics in underground hard rock mining: A question of value and vision: 66th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 2046-2047.

Yilmaz, O., 1987, Seismic Data Processing: Soc. Expl Geophysicists.