Enhancing base-metal exploration with seismic imaging[1]

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Abstract: Commencing in 1988 and continuing for 5 years, Lithoprobe acquired a series of high-resolution seismic experiments within and near base-metal mining camps in Canada, including the Abitibi subprovince of Quebec and Ontario, the world-class Sudbury Ni–Cu mining district, the Buchans mine in Newfoundland, and the Thompson Ni belt in Manitoba. This work, undertaken in close cooperation with the Geological Survey of Canada and major Canadian mining companies, stimulated an intensive and broadened series of followup studies with the common objective of assessing potential applications of multichannel seismic (MCS) imaging for deep mineral exploration and mine development. This research was motivated by a widely recognized disparity between the depths from which ores can be profitably mined (up to 2 km or more) and the resolving depths (typically <500 m) of commonly used geophysical methods for mineral exploration. Initial rock-property studies established that the expected contrast in acoustic impedance between ores and host rocks should be sufficient to generate observable reflections and (or) scattered waves. For an ore deposit to be directly detectable with MCS, however, it is also necessary for it to meet geometrical criteria including a minimum thickness of 1/8 wavelenth (typically ∼5 m) and a lateral extent similar to the Fresnel radius (typically ∼100 m). Both Lithoprobe and followup seismic studies, calibrated with borehole data, reveal that lithologic contacts that are characterized by large impedance contrast and significant lateral continuity, such as igneous intrusive contacts between mafic and felsic rocks, are the most likely features to be imaged with the MCS techniques. In some camps such as Buchans, however, faults and shear zones are better imaged than lithologic contacts. In either case, these studies show that well-designed and carefully processed seismic profiles can provide a valuable geophysical tool for interpreting the stratigraphic and structural framework of mineral systems and, more rarely, direct-detection capabilities for deep ore deposits.

Résumé : Débutant en 1988 et se poursuivant pendant 5 ans, Lithoprobe a acquis une série d'essais sismiques de haute résolution à l'intérieur et à proximité de camps miniers de métaux de base au Canada, incluant la sous-province de l'Abitibi au Québec et en Ontario, le district minier Ni–Cu de classe mondiale de Sudbury, la mine Buchans à Terre-Neuve et la ceinture de nickel Thompson au Manitoba. Ce travail, entrepris en collaboration étroite avec la Commission géologique du Canada et de grandes compagnies minières canadiennes, a stimulé une série d'études de suivi, intensives et élargies, dont l'objectif commun était d'évaluer des applications potentielles d'imagerie sismique par canaux multiples « MCS – Multichannel Seismic » pour l'exploration minérale en profondeur et le développement de mines. Cette recherche a été motivée par la disparité largement reconnue entre les profondeurs desquelles les minerais peuvent être extraits rentablement (jusqu'à 2 km ou plus) et les profondeurs de résolution (typiquement < 500 m) des méthodes géophysiques courantes pour l'exploration minérale. Les premières études de propriétés des roches ont établi que le contraste attendu en impédance acoustique entre les minerais et les roches mères devrait être suffisant pour générer des réflexions observables et (ou) des ondes dispersées. Pour qu'un gisement puisse être directement détectable grâce à l'imagerie sismique par canaux multiples, il est toutefois nécessaire qu'il rencontre des critères géométriques dont une épaisseur minimale de 1/8 de la longueur d'onde (typiquement ∼5 m) et une étendue latérale semblable au rayon de Fresnel (typiquement ∼100 m). Lithoprobe et les études sismiques de suivi, calibrées avec des données de forages, révèlent que les contacts lithologiques sont caractérisés par un fort grand contraste d'impédance et une importante continuité latérale; par exemple, les contacts intrusifs ignés entre les roches mafiques et felsiques sont les caractéristiques probablement les mieux imagées avec des techniques d'ima-

Received 3 September 2009. Accepted 3 September 2009. Published on the NRC Research Press Web site at cjes.nrc.ca on 28 January 2010.

Paper handled by Associate Editor R. Clowes.

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[1]This article is one of a series of papers published in this Special Issue on the theme *Lithoprobe — parameters, processes, and the evolution of a continent*.
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gerie par canaux multiples. Dans certains camps, tels que celui de Buchans, les failles et les zones de cisaillement sont toutefois mieux imagées que les contacts lithologiques. Dans les deux cas, ces études démontrent que des profils sismiques bien conçus et bien traités peuvent fournir un outil géophysique intéressant pour interpréter le cadre stratigraphique et structural des systèmes minéraux et, plus rarement, permettre la détection directe de gisements profonds.

[Traduit par la Rédaction]

Introduction

Mining of base metals, including Cu, Zn, Ni, and Pb, makes a vital contribution to the Canadian economy, particularly in northern regions of the country. Since the majority of the most accessible and shallowest targets for exploration have most likely been discovered, the development of geophysical methods that can detect and (or) delineate deep ore deposits is of growing societal, as well as scientific, interest. A significant gap remains, however, between the maximum depths from which ores can be profitably mined (>2 km in many cases) and the effective penetration depths of traditional geophysical methods used in mineral exploration, such as controlled-source electromagnetics, induced polarization, and resistivity survey methods (<0.5 km in most cases; see Eaton et al. 2003).

As part of Lithoprobe's interdisciplinary program of geoscientific research, high-resolution multichannel seismic (MCS) surveys were acquired in mining regions across Canada (Fig. 1), with the objective of evaluating potential effectiveness as a deep mineral exploration tool (Clowes 1994, 2001). These Lithoprobe studies were focused on regions surrounding mine infrastructure to maximize the use of the existing resources. This work provided the impetus for several large, multidisciplinary followup projects in Sudbury and Manitouwadge (Ontario), Matagami and Louvicourt (Quebec), and Bathurst (New Brunswick). Taken together, these investigations have contributed a great deal to our understanding of cost-effective approaches to seismic survey design, processing, modelling, and interpretation of unconventional seismic data (in the sense that the vast majority of seismic data is acquired within sedimentary basins), and the physical basis of seismic reflections in hardrock terranes. Table 1 summarizes acquisition parameters used for Lithoprobe surveys considered here; these parameters evolved through time, reflecting technological advances in the seismic industry.

The purpose of this paper is to review some of the numerous contributions made by Lithoprobe toward the development of seismic technology for deep mineral exploration. We will begin with a brief overview of the petrophysical basis for this technique, i.e., why base-metal deposits are expected to produce strong seismic reflections and (or) scattered signals. Next, we will consider case studies that illustrate Lithoprobe results, with a view toward both the potential for, and the limitations of, MCS applied to mineral deposit exploration and development. Lastly, we will summarize a few representative Lithoprobe followup projects, including how these studies fit into the global context and future prospects for MCS survey techniques as a cost-effective tool for deep mineral exploration and orebody delineation.

Petrophysical basis for seismic exploration

During the course of laboratory studies of the acoustic properties of rocks in the Sudbury Basin, it was discovered, almost by accident, that massive sulphides should make strong reflectors in many geologic settings. Systematic studies of the velocities and densities of massive sulphides and common rocks at elevated confining pressures (Salisbury et al. 1996) showed that sulphide ores invariably lie far to the right of the Nafe–Drake curve (Ludwig et al. 1971) in cross plots of velocity versus density (Fig. 2). In general, ores occupy a field controlled by the end-member properties of pyrite, pyrrhotite, chalcopyrite, and sphalerite. Ores rich in pyrrhotite tend to fall along mixing lines between pure pyrrhotite and mafic host rocks; whereas ores rich in pyrite, sphalerite, and chalcopyrite fall on mixing lines with felsic igneous rocks. Of particular significance, many ores, especially those containing pyrite, have significantly higher acoustic impedances (Z) than the country rocks with which they are commonly associated, making them potential reflectors. An example of this can be seen in logging results from the Stratmap deposit in Bathurst (Fig. 3), which show pyrite-rich horizons with significantly higher Z than the tuffs and argillites that surround them. For normal incidence, the reflection coefficient (R) is given by

$$[1] \qquad R = \frac{Z_2 - Z_1}{Z_2 + Z_1} = \frac{V_2\rho_2 - V_1\rho_1}{V_2\rho_2 + V_1\rho_1}$$

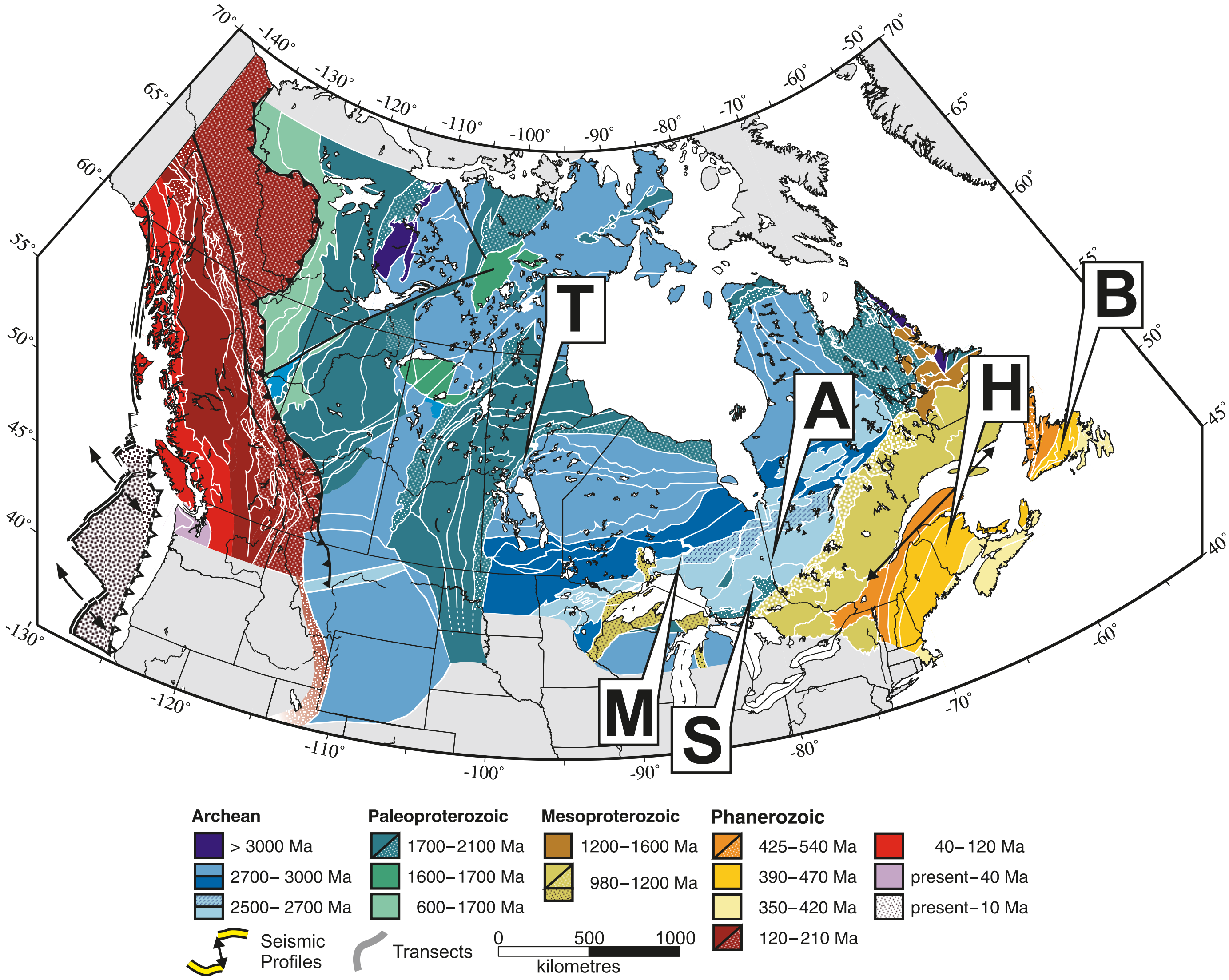
where V is the velocity and ρ is the density. In the case of most base-metal deposits, the reflection coefficient with respect to host lithologies exceeds 0.06, considered the minimum value necessary to produce an observable reflection under signal-to-noise conditions, typical of hardrock settings (Salisbury et al. 2003).

Whether an ore deposit can be directly detected and imaged also depends on its size and geometry, in particular, its thickness, diameter, and depth of burial. For the simple case of a buried tabular or disc-shaped deposit, the minimum thickness (t_{min}) that can be reliably resolved can be estimated from the criterion

$$[2] \qquad t_{\min} = V/(8f)$$

where V is the average formation velocity and f is the dominant frequency (Widess 1973; Chopra et al. 2006). While it is theoretically possible to detect thinner deposits, the amplitude will be gradually reduced due to phase inversions by destructive interference of reflections from the upper and lower contacts with the country rock. The nature and amplitude of the reflection from a deposit also vary with its depth and diameter. For example, at a given depth (z), the smallest diameter deposit that can be imaged, as opposed to merely detected, can be estimated from the relation

Fig. 1. Location of high-resolution seismic studies discussed in this paper, superimposed on a crustal age map of Canada. A, Abitibi subprovince (including Matagami, Selbaie, Noranda, and Louvicourt study areas; see Fig. 7); B, Buchans; H, Half Mile Lake (Bathurst mining camp); M, Manitouwadge; S, Sudbury; T, Thompson.



[3] $d_F = (2zV/f)^{1/2}$

where d_F is the diameter of the first Fresnel zone. Neglecting curvature (cf. Eaton 2006), the Fresnel diameter also provides an approximate measure of the minimum lateral dimension of an interface whose amplitude is representative of the impedance contrast of the reflector. Smaller diameter deposits can be detected but appear in unmigrated seismic images as diffractors rather than reflectors.

In practice, other factors can complicate the use of seismic-reflection techniques for base-metal exploration. These factors include small-scale lithologic heterogeneity, which can reduce the signal-to-noise ratio of the reflections from sulphide deposits; steep dip, which will shed reflections away from the receiver array; and structural complexity, which can make a reflective deposit appear "diffractive." Because of these complications, MCS methods were limited in many of the settings examined to map geologic structure and trace stratigraphic horizens on which ore deposits are known to occur. Under favourable circumstances, such as the Bathurst Mining Camp and Louvicourt, deposits have been detected and imaged directly (Salisbury et al. 2003; Adam et al. 2007).

Buchans

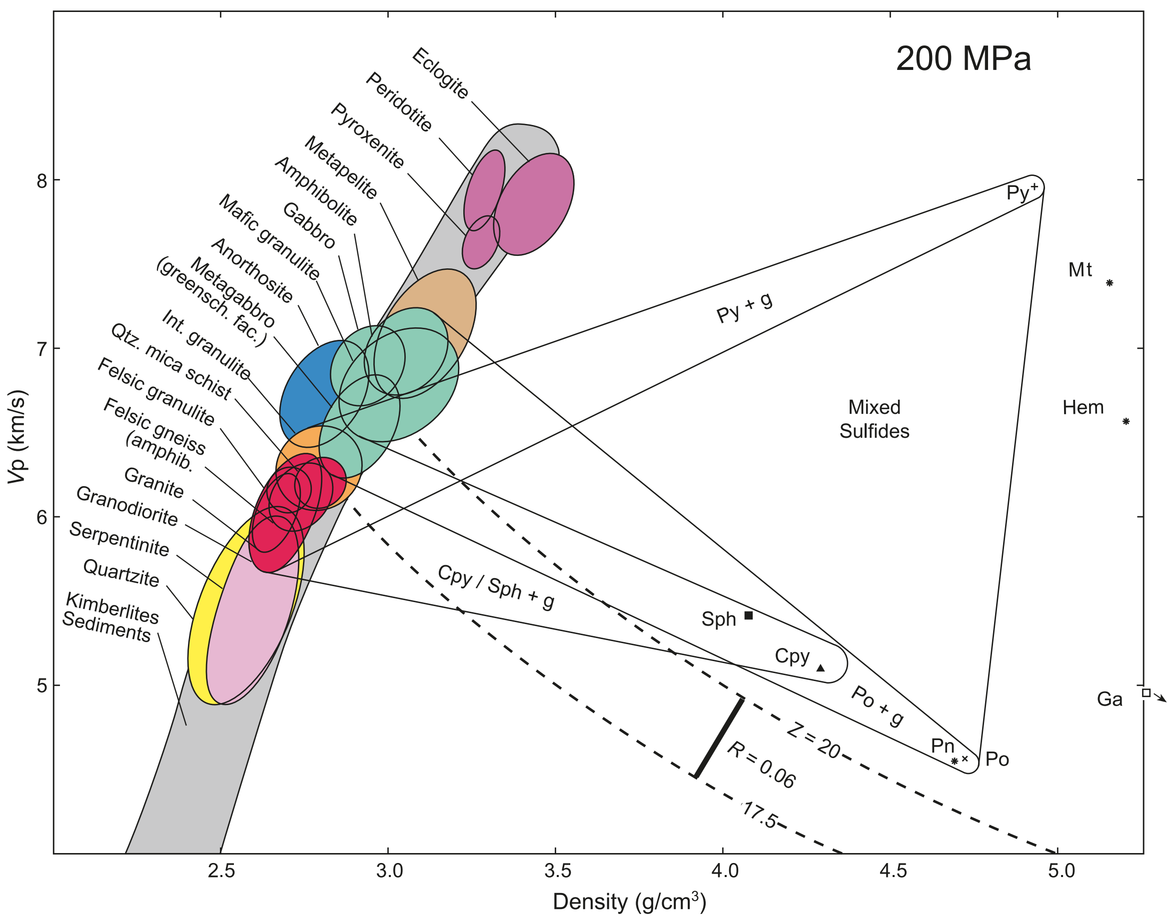
Some of the earliest studies of the effectiveness of the MCS reflection method for mineral exploration were conducted at the ASARCO mine at Buchans, Newfoundland. The Buchans Mine produced ore continuously for over 50 years until its closure in the late 1970s (Thurlow and Swanson 1981). The first reflection seismic surveys at Buchans were conducted at Memorial University of Newfoundland in the mid-1980s on behalf of BP Minerals, who had taken the exploration rights for the property. The Lithoprobe East program (Fig. 4) included the acquisition of the first major Vibroseis reflection survey at a mine site in North America, at the Buchans Mine. In all, 16 km of high-resolution seismic profile data were acquired (Spencer et al. 1993).

The Buchans site is an excellent location to study the ef-

Table 1. Acquisition parameters for Lithoprobe high-resolution surveys.

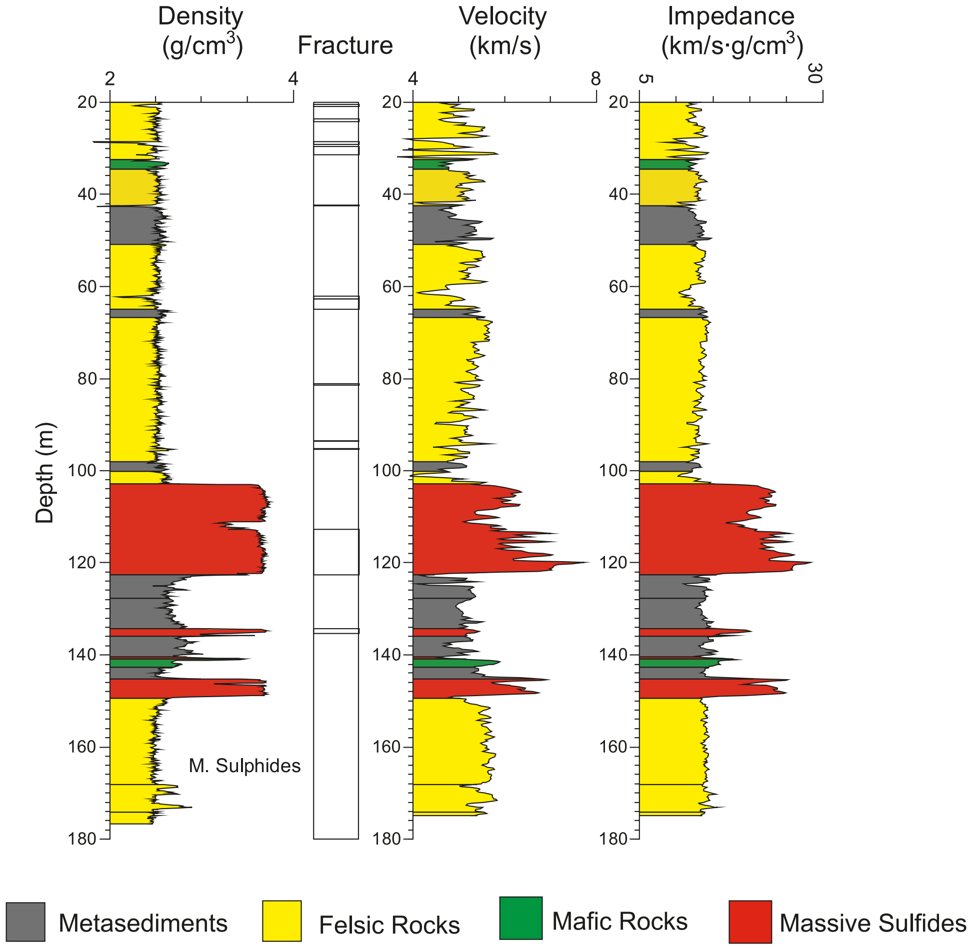
	Lithoprobe East	Abitibi–Grenville (phase I)	Abitibi–Grenville (Phase II)	Trans-Hudson Orogen
Year of survey	1989	1990	1993	1991
Figure No.	5	9	6, 8	12, 13
S–P interval (m)	20	20	20	20
Sweep frequencies (Hz)	40–130	30–140	30–135	30–130
No. of sweeps	4	2	4	4
Sweep length (s)	10	12	12	12
Source pattern (No. of Vibroseis / length in m)	2/20	2/20	3/18	4/50
Instrumentation	DFS V	SERCEL	MDS-18X	MDS-18
Correlated record length (s)	16	4	4	4
Sample interval (ms)	2	2	2	2
Geophone type	Mark L28	Mark L25	Mark 125D	OYO 20D
Geophone frequency (Hz)	14	30	30	30
Group interval (m)	10	20	8	20
No. of channels	240	240	240	240
Maximum offset (m)	1610	2400	2400	3200
Spread type	Asymmetric split	Symmetric split	Symmetric split	Asymmetric split

Fig. 2. Plot of compressional wave velocity (*V*p) versus density, showing the Nafe–Drake curve for common silicate rocks, as well as values for the minerals pyrite (Py), sphalerite (Sph), chalcopyrite (Cpy), pyrrhotite (Po), pentlandite (Pn), galena (Ga), magnetite (Mt), and hematite (Hem). Also shown are fields for common ore – host rock mixtures and lines of constant acoustic impedance ($Z \times 10^4$ kg·m^{-2}·s^{-1}). An impedance difference of 2.5 corresponds to a reflection coefficient (*R*) of 0.06, which is considered sufficient to cause strong reflections. From Salisbury and Snyder (2004, reproduced with permission of Geological Association of Canada). amphib., amphibolite; fac., facies.



fectiveness of the MCS method for mineral exploration, as the geology is well mapped through an extensive set of surface observations, drill holes (most of which are fully cored), and underground mine workings. The structural setting is interpreted as an imbricated set of thrust stacks (Thurlow and Swanson 1981; Calon and Green 1987). The

Fig. 3. Log-derived density, positions of major fractures, compressional wave velocity, and compressional wave elastic impedance for the Stratmat main zone deposit in Bathurst, hole St221. Comparison of the impedance log with lithology suggests that the massive sulphides will make strong reflectors. Modified from Schmitt et al. (2003).



ore zones comprised a set of polymetallic volcanogenic massive sulphide (VMS) orebodies hosted by felsic pyroclastic rocks and breccias of the Lower Ordovician Buchans Group. The orebodies occur within a major duplex structure that is floored by an out-of-sequence thrust fault, the Powerline thrust (Thurlow et al. 1992). In this igneous–metamorphic setting, the formations juxtaposed across the thrusts have similar acoustic impedances; thus, the seismic targets were the thrust faults and not the orebodies per se. Any reflection signature of the faults is more likely due to the highly fractured material in the fault zone (sometimes up to tens of metres thick) than to the differential geology across the fault (Thurlow et al. 1992).

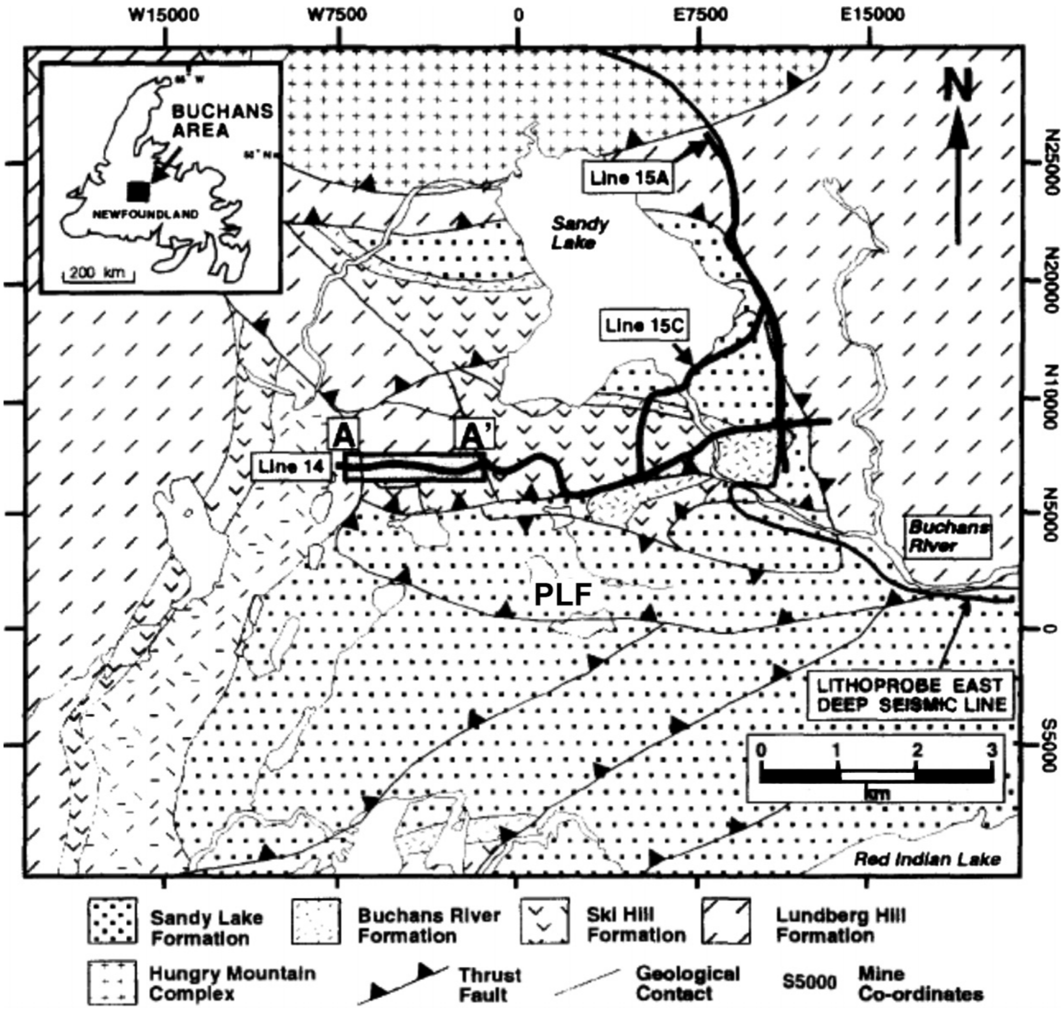
Prominent reflections from faults and shear zones were revealed by the Lithoprobe profiles (Fig. 5), the interpretation of which was important for understanding the architecture and structural evolution of the deposit at mine and regional scales. In particular, major faults, including the Old Buchans Fault (<500 m depth) and the Powerline Fault (~1000 m depth), were reasonably well imaged although detail on the fault surfaces was not resolved (Boerner et al. 1990; Thurlow et al. 1992; Spencer et al. 1993). Seismic mapping of the Powerline Fault, which truncates the orebodies at depth, provided important (albeit negative) constraints on the extent of prospective strata for exploration.

The Lithoprobe East high-resolution surveys at Buchans were sufficiently encouraging that a group from CERR extended the research to investigate the effectiveness of different seismic sources and processing techniques (Wright et al. 1994). The two major constraints on the use of Vibroseis for mineral exploration were the mobilization cost of the source units and the inherent frequency limitation available in the early 1990s (60–125 Hz). Efforts to extend the spectrum of Vibroseis data beyond these limits were not successful. To address these constraints, CERR acquired seismic data along the same line (14) as one of the Lithoprobe lines. The source consisted of a small (40 g) charge in a two-hole pattern buried at a depth of ~0.7 m. This source generated useful source signal after spectral balancing from 60–240 Hz — one octave more than for Vibroseis. Careful processing of these data showed good signal strength and spectral quality well over 0.5 s two-way traveltime (TWT; ~1000 m). Similar source parameters for explosive surveys have later been used in Sweden for nuclear waste disposal site studies (e.g., Bergman et al. 2002; Juhlin and Stephens 2006).

Sudbury

The Sudbury Basin has been actively mined for over a century and is the richest Ni-producing area in the world.

Fig. 4. Generalized geology of the Buchans mine region, showing location of the Lithoprobe seismic lines (Wright et al. 1994, reproduced with permission of Elsevier). The coincident Memorial University's Centre for Earth Resources Research (CERR) dynamite profile is marked as A–A′. PLF, Powerline Fault.



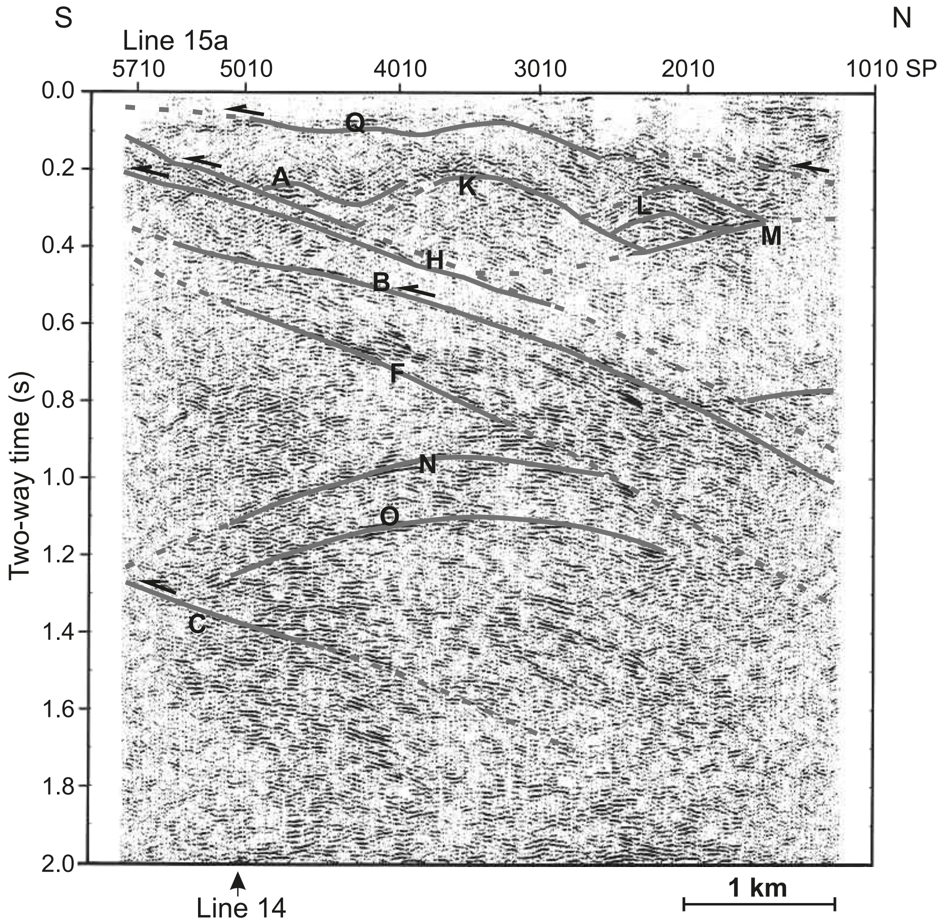
Ni–Cu orebodies occur near the base of the Sudbury Igneous Complex (SIC), a major layered igneous complex, as well as in proximal basement rocks that form the SIC's footwall (Morrison 1984). Based largely on the abundance and distribution of shock-deformation fabrics, the SIC is interpreted by most researchers as a crustal melt sheet generated by a giant impact event, ca. 1.85 Ga (Dressler et al. 1992). The present-day quasi-elliptical outline of the Sudbury Basin reflects postimpact crustal-scale penetrative deformation that occurred during the Penokean Orogeny (Wu et al. 1995).

Although known ore reserves will not be depleted for decades, there is a long-standing interest to develop more effective geophysical techniques to locate new deposits to depths of at least 2500 m, the limit that modern mining methods are capable of economically extracting ore in the Sudbury mining camp (Adam et al. 2000). This prompted the acquisition of Lithoprobe high-resolution MCS surveys across the Sudbury Basin in 1988 and 1991 (Fig. 6*a*). A particularly exciting early result from these investigations was the observation of prominent diffractions (a special case of scattering) from the dipping Creighton 402 orebody (Fig. 6*b*) located at a depth of >2 km beneath the southern rim of the Sudbury Basin. Observed scattered waves[3] from the Creighton 402 orebody appear to be divisible into two components, one originating from the unmined ores and the other originating from the mined-out part of the deposit that has been backfilled with concrete. This provided a compelling demonstration of the potential utility of MCS methods as a direct-detection tool for base-metal deposits.

During the years following Lithoprobe's two phases of seismic data acquisition in the basin, a comprehensive program of physical-property measurements was undertaken by the Geological Survey of Canada. An extensive database of new and existing geological mapping results, borehole logs, and physical rock property studies on core samples was assembled to support interpretation of the seismic data (e.g.,

[3] In the seismological literature, the terms scattering and diffraction are used in different ways by different authors. Here, scattering is used to denote the theoretical difference between a reference wavefield in a homogeneous medium and the wavefield in the actual (inhomogeneous) medium; diffraction is used to describe scattering from a relatively isolated inhomogeneity, whose maximum dimension in any direction is not greater than a Fresnel diameter. In this context, diffraction is a subset of scattering.

Fig. 5. Coherency-filtered data from line 15a of the Buchans survey and its geological interpretation (after Thurlow et al. 1992). The Powerline Fault (B and F), which floors the ore-hosting stratigraphy, is visible as a 0.1 s north-dipping band of reflectivity that underlies a seismically transparent section and truncates antithetic (south-dipping) fault zones (M, N, and O). This structural relationship supports an interpretation of the Powerline Fault as an out-of-sequence thrust. Strong scattered signals at relatively shallow depth (A, K, and L) lie in the footwall of the Airport Thrust (A). Like the Airport Thrust, the regionally significant Victoria River Delta Fault (C) appears as a conspicuous, gently north-dipping band of reflectivity.



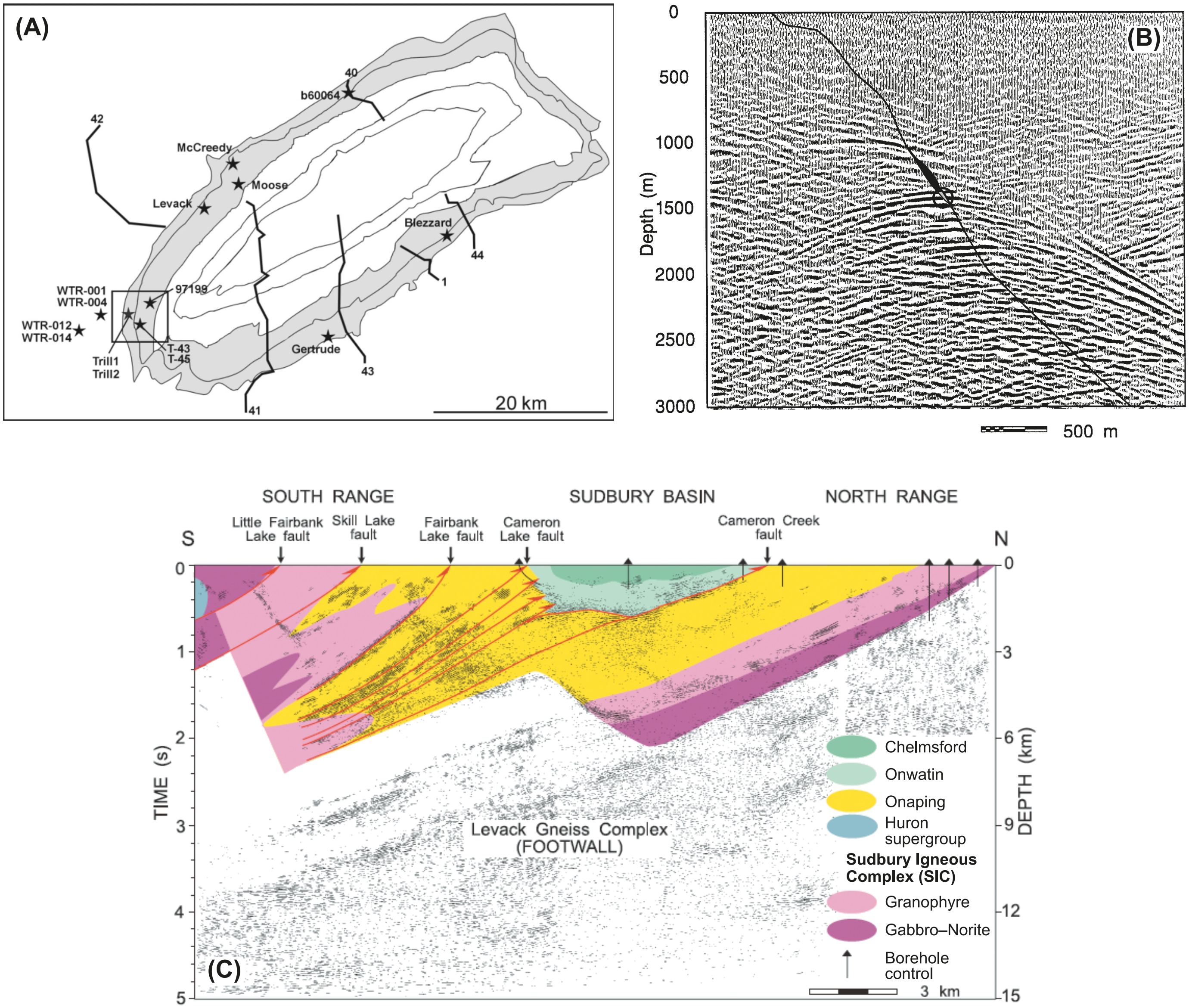
White et al. 1994). These studies revealed that Sudbury norite, a melt phase that dominates the deeper half of the SIC, is effectively homogeneous from a seismic perspective with *P*-wave velocities and densities falling in a narrow range of 6200–6400 m/s and 2.75–2.8 g/cm^3, respectively (Adam et al. 2000). On the other hand, the underlying sublayer and footwall complex display more significant velocity and density variations (6000–6700 m/s and 2.75–3.0 g/cm^3, respectively).

These petrophysical characteristics derived from core and logging studies suggest that the contact between the "transparent" SIC norite and the "reflective" footwall complex represents an identifiable regional marker horizon, making it possible to map the base of the SIC, where Ni–Cu deposits are predominantly located. This scenario was borne out by high-resolution seismic images (Fig. 6*c*), which, taken together, provide a spectacular cross section spanning the Sudbury Basin (Wu et al. 1995). This profile revealed a profound asymmetry of the Sudbury Structure. More importantly, the seismic images showed that large-scale shortening of the structure was accommodated by both ductile folding as well as late brittle thrust faulting (Fig. 6*c*). The recognition of the role of brittle faulting, which dissects the isoclinal folds and nappe structures in the South Range, has direct economic implications because it means that the main ore-bearing horizon (Sudbury sublayer) may be duplicated at mineable depths in the southwest corner of the SIC (Wu et al. 1995).

Abitibi region of northwestern Quebec

The Abitibi subprovince, the largest Archean greenstone belt in the world, is bounded to the south by the metasedimentary Pontiac subprovince, to the north by the Opatica plutonic belt, to the east by the Grenville Province, and to the west by the Kapuskasing structural zone. Lithologic assemblages and primary structures within the Abitibi subprovince are relatively well preserved due to the paucity of high-grade metamorphism. Volcanic and intrusive rocks in the Abitibi subprovince have crystallization ages ranging from 2740 to 2640 Ma (Ludden et al. 1993). The origin of the subprovince is attributed to accretion of a series of volcanic island arcs (Hoffman 1991). This tectonic setting provided geological environments that were favorable for the

Fig. 6. (A) Map of high-resolution multichannel seismic profiles acquired by Lithoprobe across the Sudbury Basin. (B) Unmigrated image showing scattering from the Creighton 402 orebody. Line shows base of the Sudbury Igneous Complex (SIC), black region shows ore remaining in the Creighton 402 orebody at the time of the seismic survey, and circled gray region shows the mined-out section of the orebody. Note conspicuous scattering from the deposit. (C) Interpreted seismic cross section across the Sudbury Basin (after Wu et al. 1995).



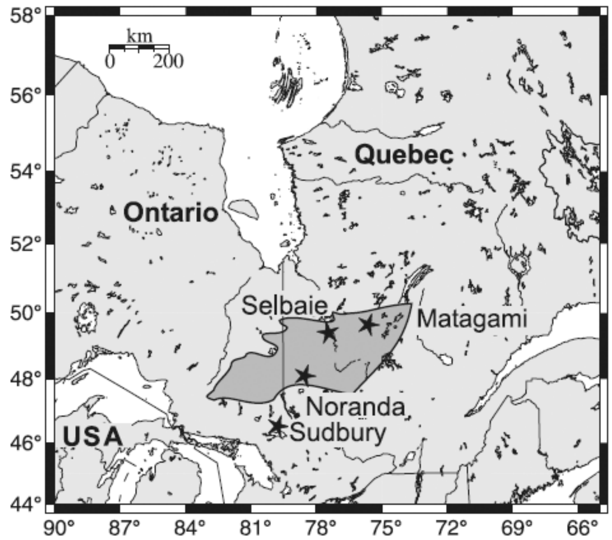
formation, accumulation, and preservation of precious and base-metal deposits (Franklin et al. 1981).

Between 1988 and 1993, Lithoprobe conducted high-resolution surveys at three major base-metal mining camps in the Abitibi subprovince. Barnes et al. (1995) presented an exhaustive appraisal of the Abitibi–Grenville seismic acquisition parameters; hence, seismic data acquisition is not discussed here. Although the Abitibi region contains globally significant gold reserves, none of the Lithoprobe detailed investigations was designed to image these deposits, since they tend to be controlled by near-vertical regional faults that are difficult to image seismically. Only one high-resolution seismic line, acquired in 1988, crossed a known gold-bearing structure (the Larder Lake – Cadillac Fault). Lithoprobe's high-resolution MCS program focused instead on the utility of seismic methods as an exploration and development tool for VMS deposits.

Matagami

The Matagami mining camp forms part of the volcano-sedimentary Harricana–Turgeon belt in the northwestern part of the Abitibi subprovince (Lacroix et al. 1990). The Matagami volcanic complex was formed by two major phases of volcanism: the early phase produced rhyolites of the Watson Lake Group and the second was dominated by basaltic volcanism that formed the Wabassee Group (Beaudry and Gaucher 1986). A cherty, sulphidic chemical sediment known as the Key Tuffite, marks the contact and hiatus between these two groups. This thin horizon (0.6–6 m) is the primary exploration target because it hosts most

Fig. 7. Location of mining camps in and around the Abitibi subprovince.



of the orebodies discovered in the camp (Piché et al. 1993). The volcanic rocks in our study area are weakly deformed and dip ~45° toward the southwest (Piché et al. 1993).

The Matagami mining district was in uninterrupted production between 1963 and 2004 and is well known for VMS deposits with high zinc content (Sharpe 1968). The principal exploration strategy for locating VMS deposits was to drill into footwall rock units in an attempt to intersect an alteration pipe and, through the use of borehole electromagnetic measurements, to test for the presence of conductive massive sulphides above the borehole. This exploration methodology has been employed by Noranda since early 1990s in the Matagami mining camp and is similar to that described by Boivin and Lambert (1997).

In 1992, just prior to the acquisition of Lithoprobe data, the Bell Allard deposit was discovered. Bell Allard is located at the Key Tuffite, atop a synvolcanic fracture zone characterized by classic hydrothermal alteration. The orebody is ~370 m long and 165 m wide in the downdip direction. Sulphide mineralization consists of pyrite, Fe-rich sphalerite, minor chalcopyrite, and pyrrhotite. Thickness averages 30 m but can range up to 60 m in portions of the south lens. The deposit dips 50°–55° towards the south between depths of 900 and 1150 m. Reserves of 3.2 million tonnes grading 13.77% Zn, 1.50% Cu, 43.45 g/t Ag, and 0.76 g/t Au have been identified to date.

Two high-resolution Lithoprobe seismic profiles (lines 29-3 and 93a) were acquired in this area. The objective of line 29-3, acquired in 1990, was to map the Key Tuffite where borehole control was unavailable. In 1993, a second Lithoprobe seismic profile (line 93a) was acquired above the newly discovered Bell Allard deposit to test the possibility of direct detection using seismic-reflection technology. To aid in interpretation of the seismic data and to better understand the high reflectivity of the volcanic sequence, a comprehensive physical rock-property study was undertaken using both in situ (Milkereit et al. 1992*b*; Adam et al. 1998) and core measurements (Adam et al. 1996, 1997). These studies showed that rhyolites exhibit the lowest acoustic impedance, whereas the highest are associated with pyrite-rich sulphides and magnetite-rich gabbros. Thus, strong reflections are expected from the contacts between rhyolites and gabbros or pyrite-rich massive sulphides.

The seismic section obtained by prestack migration of line 93a (Fig. 8) shows a detailed image of the volcanic strata and gabbro sills that intrude it (Calvert and Li 1999). Faulting can be inferred from discontinuities in these reflections, although the exact position of the faults in three dimensions is unclear because the seismic profile is oblique to the predominant dip direction. The location of the contact between the lower Wabassee and the Watson groups is interpreted to be parallel to reflections from the volcanic strata, at a depth defined by borehole data and the intersection with line 29-3.

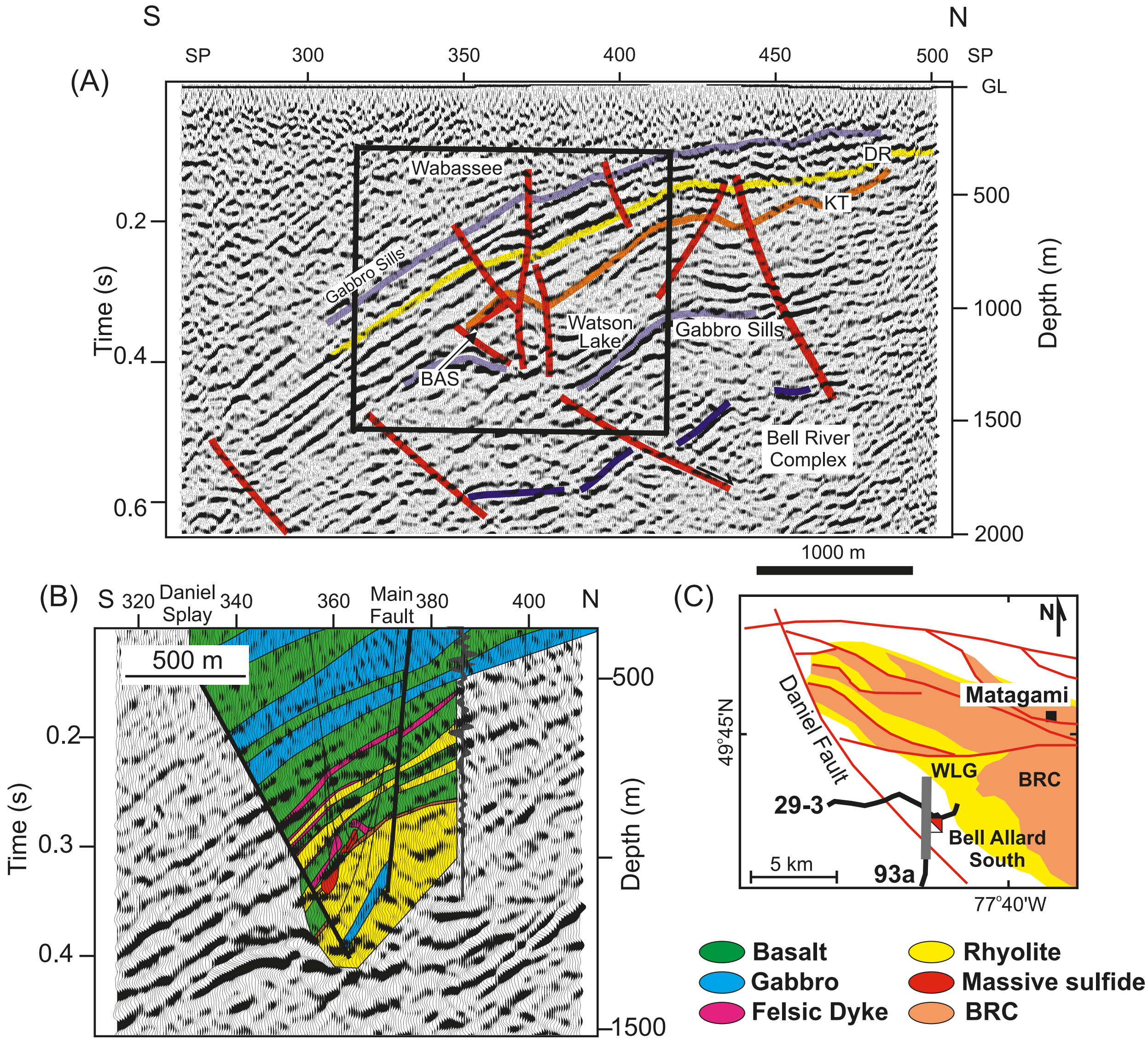
A strong reflection originating from the top of the Bell Allard deposit is identified at the intersection of a low-angle normal fault with the top of the Watson Lake Group (Fig. 8). This indicates that sulphide mineralization may have been controlled by fluid flow along the fault, which likely penetrates to the underlying mafic intrusion. The reflection from the orebody does not appear to extend over its full width, as defined by drilling but rather appears to be restricted to the lower, pyrite-rich zone. Although the orebody reflection is strong (as expected), it is of comparable amplitude to other reflections recorded in the mining camp, particularly those from the gabbro sills. Thus, it is difficult, based on reflection amplitude alone, to distinguish ore reflections from other types of reflections. This ambiguity in seismic response may be resolved by considering other types of geophysical data, such as electromagnetic (see the Thompson section in this paper).

Selbaie

The Selbaie mine (47.3 Mt) is a polymetallic deposit within a caldera environment that has been in production for 23 years. At the mine, mineralization occurs in veins that cut the local strata at a high angle (Bouillon 1990). Two high-resolution MCS profiles (29-1, 29-2) were acquired by Lithoprobe at Les Mines Selbaie in the fall of 1990 (Milkereit et al. 1992*a*). The two east–west seismic profiles extend for >6 km over the mining camp, which consists of an Archean caldera primarily containing felsic infill (Larson 1987). The Selbaie seismic surveys were designed to map the contact boundaries of the host rock (Brouillan tonalite) in the mine area and to extend this information beyond the limits of drilling to develop strategies for future exploration. Direct imaging of sulphide mineralization was not expected because the sulphides occur in veins (Bouillon 1990).

The main challenge of this experiment was to obtain high-quality seismic images at an active mine site in the presence of high noise levels from underground workings, open pit operations, high-voltage power lines, and the mine concentrator. These noise problems were overcome using high-fold data (120) (Perron et al. 1997), and reflections observed on the seismic sections were correlated to surface geological features (Milkereit et al. 1992*a*). Density and sonic logs were acquired in a deep (~1000 m) exploration borehole adjacent to one of the seismic profiles. Laboratory measurements (density and velocity) were also made on rock samples from the main geological units and mineral-

Fig. 8. (A) Interpreted prestack-migrated section from line 93a. Strong reflections are associated with gabbro sills and interlayered rhyolites and basalts within the Lower Wabassee Group. BAS denotes Bell Allard South; KT and DR denote Key Tuffite and Dumagami Rhyolite, respectively; Red lines denote faults; SP, shot point. (B) Detailed seismic data and geology from the vicinity of the Bell Allard ore deposit, showing region outlined by the box in (A) (modified from Calvert and Li 1999). (C) Location of lines 29-3 and 93a in relation to major geological elements of the Matagami area. Segment of the profile plotted in (A) is highlighted. BRC and WLG denote Bell River Complex and Watson Lake Group, respectively.



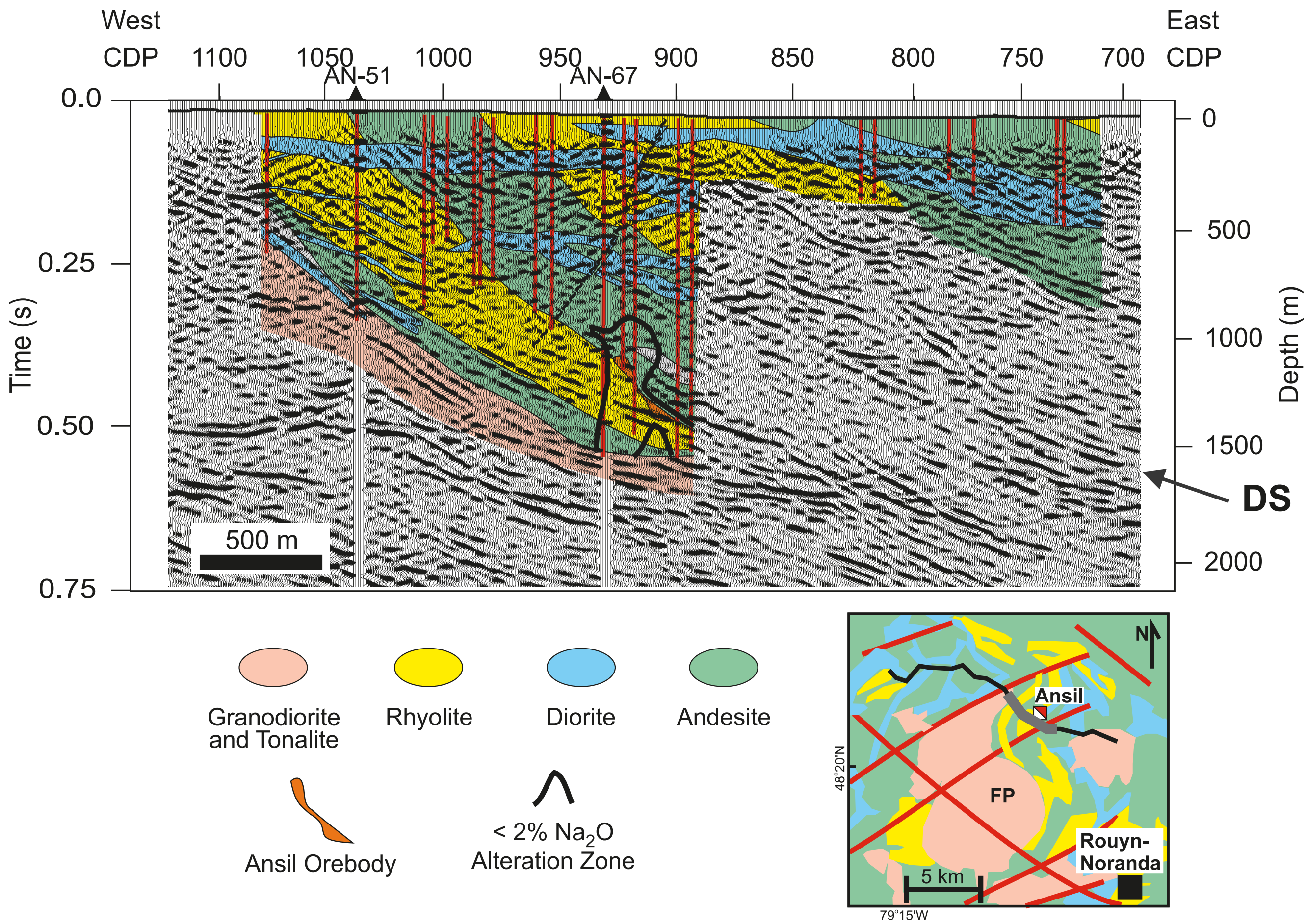
ized zones in and around the mine. With information from these physical rock-property studies, the Brouillan tonalite–andesite thrust fault suture and mafic dykes were interpreted as the main source for seismic reflections (Perron et al. 1997). The Lithoprobe studies thus helped to unravel the 3-D geometry of major rock units around the mine, as well as placing new constraints on the major tectonic events that took place at Les Mines Selbaie.

Rouyn-Noranda

The Noranda mining camp is hosted by the Blake River Group (BRG) in the southern part of the Abitibi subprovince. The BRG is the most extensive volcanic sequence found in the southern Abitibi Belt and is dominated by the Noranda Central Volcanic Complex (CVC), which consists of a bimodal sequence of rhyolite and andesite flows cored by the Flavrian pluton. The whole structure is crosscut by diorite dikes and sills. Acquisition of Lithoprobe high-resolution data in the Noranda Central Camp took place in 1988 and 1990. The 1990 survey benefited from superior data-acquisition technology compared with that used in 1988 owing to the use of a digital telemetry system with digitization at the receiver station. This technological development resulted in improved data quality and superior electrical-noise suppression. Seismic line 21-1 was acquired in 1990 across the CVC in an east–west direction. Part of this profile crosses the former Ansil mining site.

A laboratory physical rock-property study (density and compressional wave velocity; Adam et al. 1992) of 16 samples indicated that mafic intrusives (metagabbro, metadia-

Fig. 9. Portion of seismic line 21-1 over the central Noranda camp near the Ansil mine, with the geological cross section derived from borehole data superimposed (modified from Perron and Calvert 1998). The boreholes used to constrain the geological cross section are indicated by the vertical red lines. DS indicates a long, continuous reflection that extends directly into a diorite sill in the geological model. Lower right inset shows generalized geology and line location (plotted segment of profile highlighted). CDP, common-depth point; FP, Flavrian pluton.



base, and diabase) have high acoustic impedances. Reflection coefficients of up to 0.10 are expected to characterize the contact between felsic volcanic rocks and mafic intrusions. In situ density and compressional wave velocity measurements were performed in a 1677 m deep borehole located 50 m from seismic line 21-1, and densities were measured on core samples from two additional boreholes (Verpaelst et al. 1995). The diorites have the highest acoustic impedances ($\sim 23 \times 10^4$ kg·m^{-2}·s^{-1}); and rhyolites, the lowest ($\sim 18.5 \times 10^4$ kg·m^{-2}·s^{-1}) (Verpaelst et al. 1995). The acoustic impedance of basalts is $\sim 20.5 \times 10^4$ kg·m^{-2}·s^{-1}; thus, only weak reflections are expected from contacts between mafic and felsic volcanic units. Densities were measured on a total of 412 core samples (Verpaelst et al. 1995), and a statistical analysis of diorite densities revealed a bimodal distribution. A high-density population correlates with iron-rich diorites, which should, therefore, exhibit high acoustic impedance compared with other diorites. Based on these petrophysical studies, the strongest reflections in the Noranda mining camps are predicted to occur at the contact between rhyolites and iron-rich diorites.

Figure 9 shows the superposition of a geological interpretation of the Ansil mine (based on extensive borehole data) onto the high-frequency seismic profile. Discrepancies between the borehole information and the seismic data may be caused by local variations in the strike of reflecting lithological contacts, which appear as out-of-plane events. These effects must be kept in mind when the geological section derived from the borehole information and the seismic data are compared. Weak reflections are observed between volcanic rocks as predicted from the rock-property studies. Most of the strong reflections are associated with dioritic intrusions, which are generally easier to image with seismic-reflection methods because of their geometry, cutting through existing rocks in sheetlike surfaces. The nature of the contacts between the different volcanic units is probably more complex and may be related to the manner in which successive lavas were erupted and subsequently cooled to produce contacts that are laterally heterogeneous at seismic scales of investigation (Perron and Calvert 1998).

The rocks of the Flavrian pluton are spatially distributed as a series of subhorizontal tabular sills that form a genetically related group. Early fracture systems in the pluton developed in response to strain caused by regional deformation and are inferred to be precursors to the emplacement of diorite sills (Perron and Calvert 1998). At the

Pierre–Bauchemin gold mine, mineralization is associated with concordant, layered dioritic intrusions (Richard et al. 1990). Because of their high acoustic impedance, these dioritic intrusions appear in the seismic image, permitting interpretation of the shape and internal structures of the Flavrian pluton (Perron and Calvert 1998).

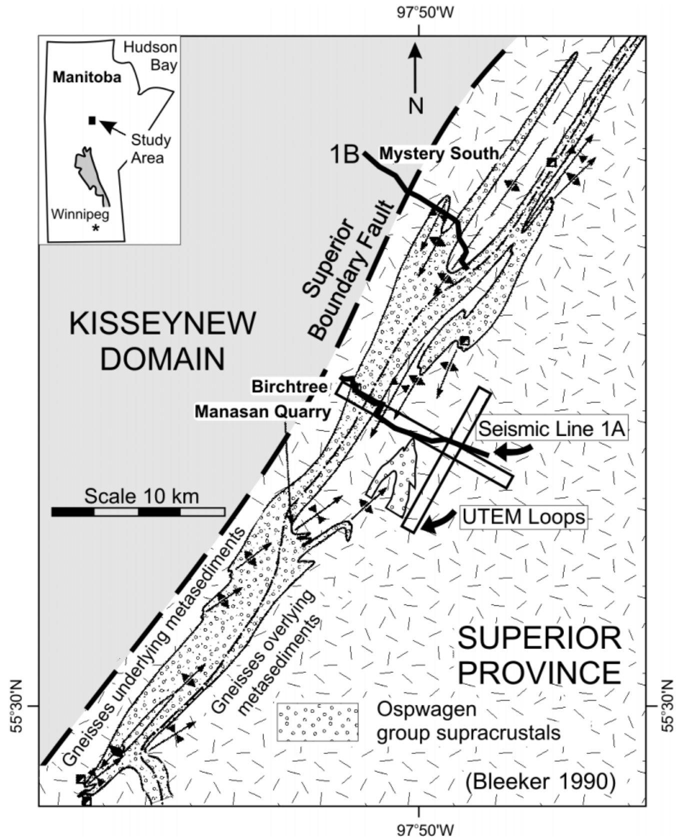
Thompson

The Thompson Nickel Belt (TNB; Fig. 10) has been a major producer of Ni from 1960s to present day. The TNB comprises variably reworked Archean gneisses interleaved and infolded with a thin Paleoproterozoic cover sequence, the Ospwagan Group (Scoates et al. 1977; Bleeker 1990*b*). All ore deposits within the TNB occur in association with ultramafic sills within the Ospwagan Group. The supracrustal rocks and ore deposits that they host have been subjected to medium- to high-grade metamorphism and intense deformation, leading to a complex interference pattern of early recumbent folds overprinted by tight, upright, doubly plunging folds and disrupted by late east-side-up ductile reverse faulting. The locations of mines around Thompson in relation to the Thompson Nappe (Bleeker 1990*a*) are shown in Fig. 11. The Birchtree mine is hosted by the lower limb of the Thompson Nappe, whereas the Thompson mine and the Owl antiform occur on later folds on an overturned limb.

In 1991, 19 km of seismic reflection data and 20 km of deep-probing electromagnetic (EM) sounding data were acquired along a common corridor in the vicinity of the Thompson mine to help constrain the interpretation of subsurface geological structures (see White et al. 1997, 2000). Subsurface mapping of the ore-hosting supracrustal rocks (Ospwagan Group) is an important element of exploration within the TNB. Coincident seismic reflection and controlled source electromagnetic data have proven to be complementary (e.g., Boerner et al. 1994). Whereas seismic images provide small-scale (10–100 m) details of density–velocity variations, electromagnetic data image resistivity anomalies that have dimensions comparable to their depth (100–1000 m). Furthermore, whereas surface seismic methods are well-suited to imaging geological features with shallow-to-moderate dips, electromagnetic data are ideally suited to imaging near-vertical features.

A composite of the seismic reflection and electromagnetic image is shown in Fig. 12, with interpretation lines superposed. Rock-property measurements indicate that the Ospwagan Group should be both relatively reflective and conductive relative to the Archean basement rocks (White et al. 2000). Both the seismic and EM images change profoundly across a steep structural zone (the Burntwood lineament). Northwest of this, the resistivity image is compromised at depth by the presence of strong shallow conductors (iron formation), and the seismic image is poor due to the presteep dips (see Fig. 13). Southeast of the lineament, the resistivity and seismic reflection fabric indicate that the rocks of the prospective Ospwagan Group extend southeastward beneath the Archean gneisses. Structural culminations that control the subsurface geometry of the Ospwagan Group (e.g., Owl Lake antiform) are generally well imaged.

Fig. 10. Study area near Thompson, Manitoba (map modified from Bleeker 1990*a*); inset shows location in Manitoba. The Thompson Nickel Belt contains the area where Ospwagan Group rocks occur east of the Superior boundary fault. UTEM, University of Toronto electromagnetic system.



Followup seismic studies undertaken as an outgrowth of Lithoprobe

The successes of Lithoprobe high-resolution MCS surveys stimulated interest in further development of seismic techniques for base-metal exploration. Applied research that ensued as a direct outgrowth of Lithoprobe continued to expand the range of techniques, beyond two-dimensional (2-D) seismic reflection profiling, to include vertical seismic profiling, downhole seismic imaging, and three-dimensional (3-D) seismic surveys. The Lithoprobe results clearly demonstrated the need for detailed, site-specific knowledge of acoustic properties of the target deposit and host rocks; thus, comprehensive physical rock-property analyses were a common element of these studies. Several of these followup experiments led to direct detection of massive sulphides. Here, three representative examples are discussed.

Manitouwadge

The Manitouwadge greenstone belt (MGB), located in northern Ontario is a highly deformed remnant of upper-amphibolite facies supracrustal rocks in the volcano-plutonic Wawa subprovince (Peterson and Zaleski 1999). The MGB is host to some major volcanogenic Cu–Zn deposits, which were all discovered at or near surface in the 1950s, including the Geco mine. The map pattern is dominated by the Manitouwadge synform, which plunges at a shallow angle

Fig. 11. Schematic cross section through the Thompson Nappe structure (Bleeker 1990*a*, with permission) along the geophysical transect showing the structural positions of the existing mines.

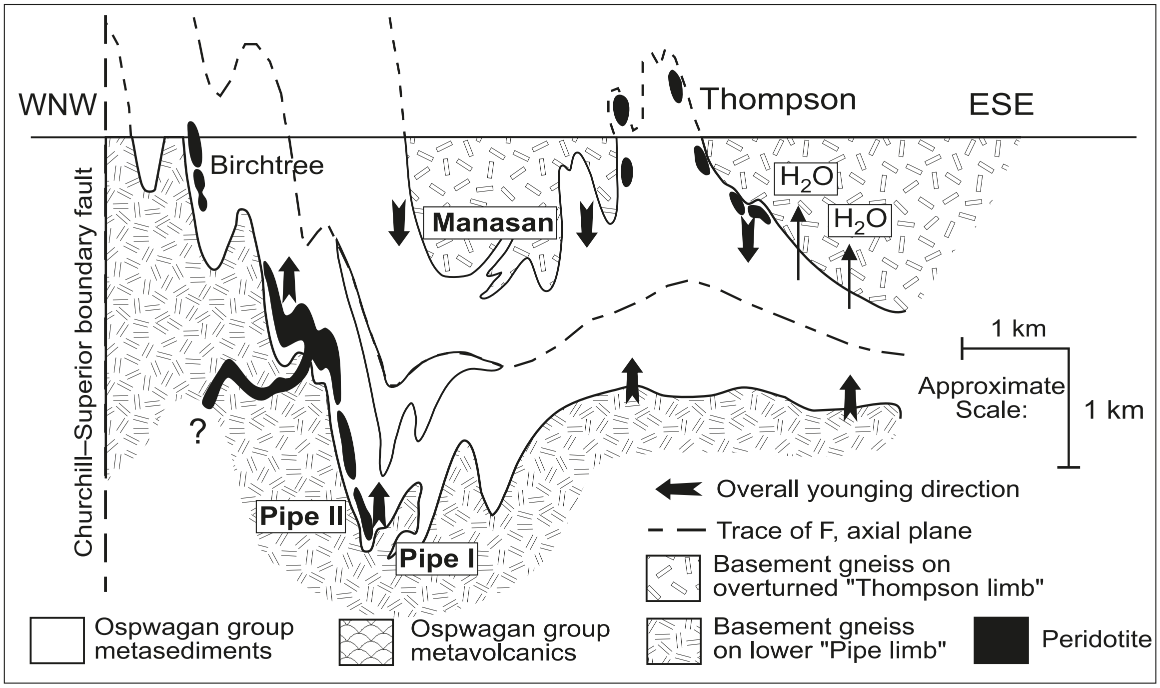
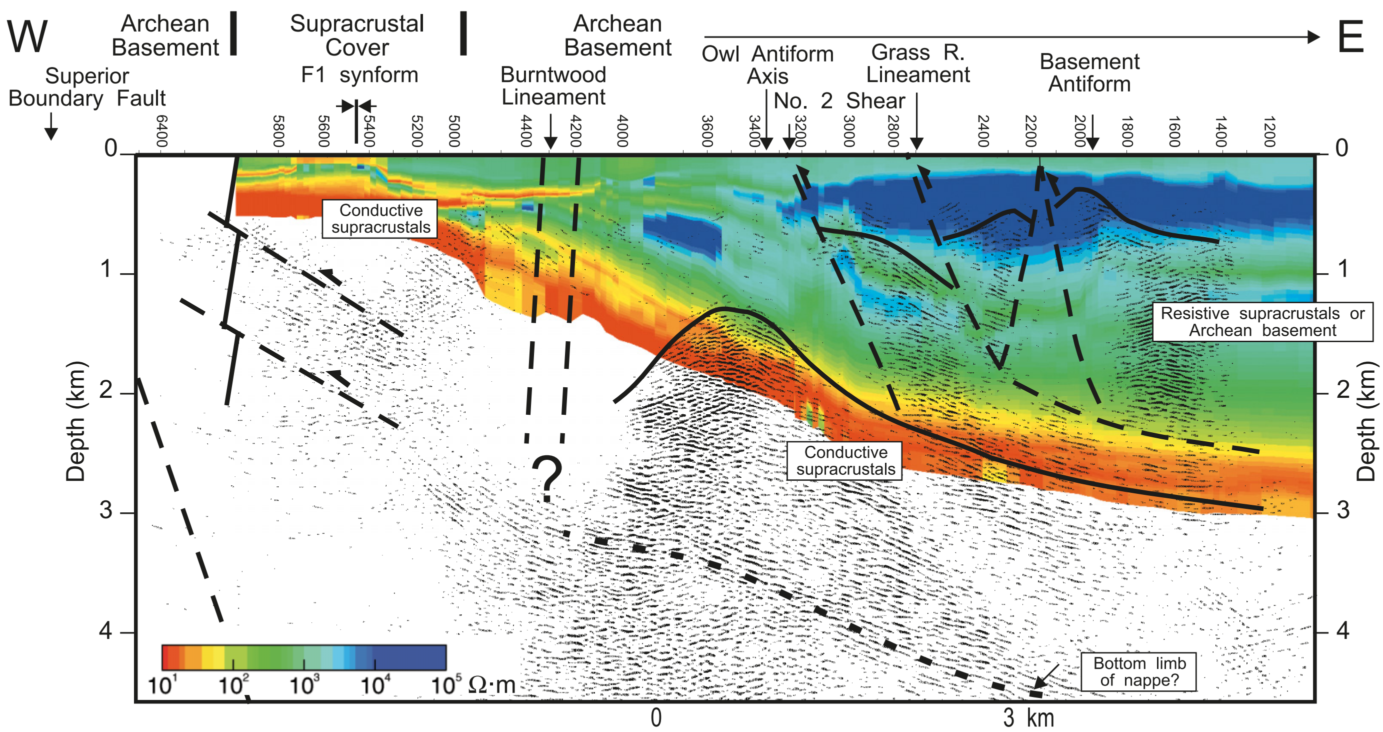


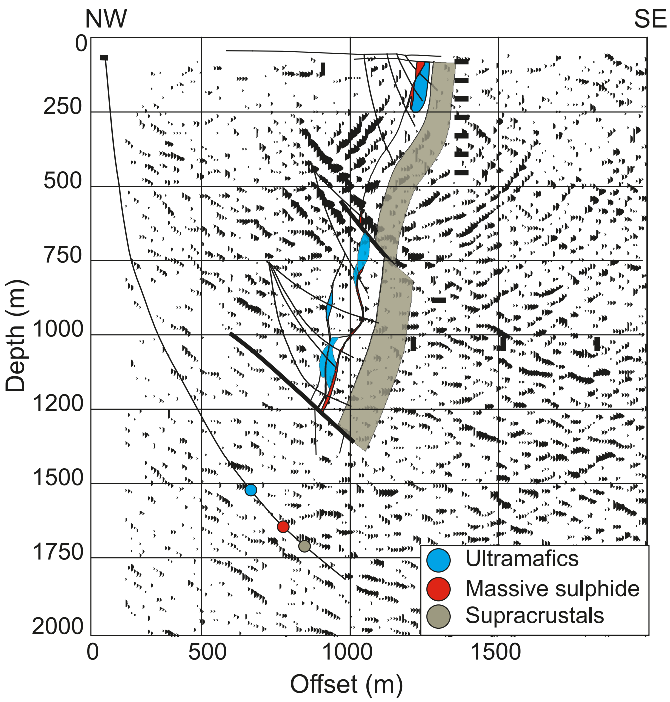
Fig. 12. Migrated seismic data superposed on the colour resistivity depth image from the coincident electromagnetic profile, Thompson Nappe structure. Seismic stations are annotated along the top of the section, as well as geologic features.



to the east-northeast, indicating relatively shallow depths to the Geco mine horizon over a considerable area (Fig. 14*a*). With the Manitouwadge belt still being highly prospective, an integrated approach was adopted to effectively image structures in such a high-grade metamorphic terrane and improve the geological model of the synform.

In 1995–1996, three 2-D seismic lines were acquired using a dynamite source in the Manitouwadge synform, the results of which, including all the presurvey studies, are reported in Roberts et al. (2003). The seismic program was successful in broadly mapping key horizons within the synform and generating several drill targets based on high-

Fig. 13. Migrated seismic data from the northwest end of the profile, Thompson Nappe structure, processed to accentuate the steeply dipping features. Geological section from boreholes is superposed for comparison. The dominant seismic reflections (SE-dipping) correspond to faults, whereas the faint steep NW-dipping reflectivity (at depths of <1000 m) corresponds to the lithologic sequences. To image the NW-dipping reflections to greater depths, the seismic line should have been extended further to the northwest. Alternatively, given the steeply dipping nature of the mine geology, vertical seismic profiling would be more effective.



amplitude anomalies. Figure 14*b* displays the western half of line 2, which runs roughly along the axial surface trace of the synform, along with a simplified geological log from borehole GS97-421. Strong reflections are correlated with the mafic volcanic rocks of the Dead Lake suite (D in Fig. 14*b*) and the contact between the felsic plutonic core of the synform and mafic meta-volcanics (V), whereas weaker, less continuous reflections can be associated with the felsic–mafic contact within the volcanic sequence (F) and the Geco mine horizon (G).

Reprocessing of previous Lithoprobe high-resolution seismic data acquired in high-grade rocks of the Kapuskasing zone demonstrated that some structures could be imaged (Wu et al. 1992), but the usefulness of the seismic technique for mineral exploration in such an environment was uncertain. The followup studies at Manitouwadge demonstrated that good impedance contrasts can exist in high-grade terranes and data with excellent signal-to-noise can be recorded. The resulting seismic profiles were effective exploration tools and provided a more complete understanding of the geological setting.

Half Mile Lake (Bathurst)

Optimal imaging of complex geological structures requires the use of 3-D seismic methods, which are capable of accurate imaging in any direction (e.g., Eaton et al. 1997; Milkereit et al. 2000; Adam et al. 2003). An excellent demonstration of this imaging capability is provided by investigations at the Half Mile Lake Cu–Zn VMS deposit in the Bathurst camp in northern New Brunswick. Country rocks in this region consist of Ordovician–Cambrian greenschist-facies metasediments, rhyolites, basaltic andesites, and gabbros (Fig. 15; Adair 1992). Despite the multiple host-environment lithologies, the average impedance of mafic rocks at Half Mile Lake ($\sim 17.5 \times 10^5$ g/cm^{2}s) due to retrograde metamorphism is only slightly higher than that of the felsic rocks (Salisbury et al. 1997). On the other hand, massive sulphides in the area are characterized by significantly higher acoustic impedance owing to their high pyrite content. Consequently, based on laboratory studies, it was determined that massive sulphide deposits should stand out as anomalous reflectors–scatterers within a seismically transparent host medium, making the camp an ideal environment for seismic prospecting. This prediction was confirmed by logging, vertical seismic profile (VSP), and 2-D seismic reflection profiling over the Half Mile Lake deposit (Salisbury et al. 2003).

Encouraged by these results, Noranda and the Geological Survey of Canada acquired a 3-D MCS survey in the area and identified two promising reflectors. Drilling revealed that one of the reflectors was produced by strong seismic anisotropy within a fault zone, a factor that had previously not been considered. The second reflector, however, was proved by drilling to be a large, formerly undetected massive sulphide deposit downdip from the Half Mile Lake orebody at a depth of 1300 m (Fig. 16). Although the deposit was determined to be too rich in pyrite to be economically viable, this case study nevertheless represented the first discovery of a massive sulphide deposit through the use of MCS techniques (Matthews et al. 2002).

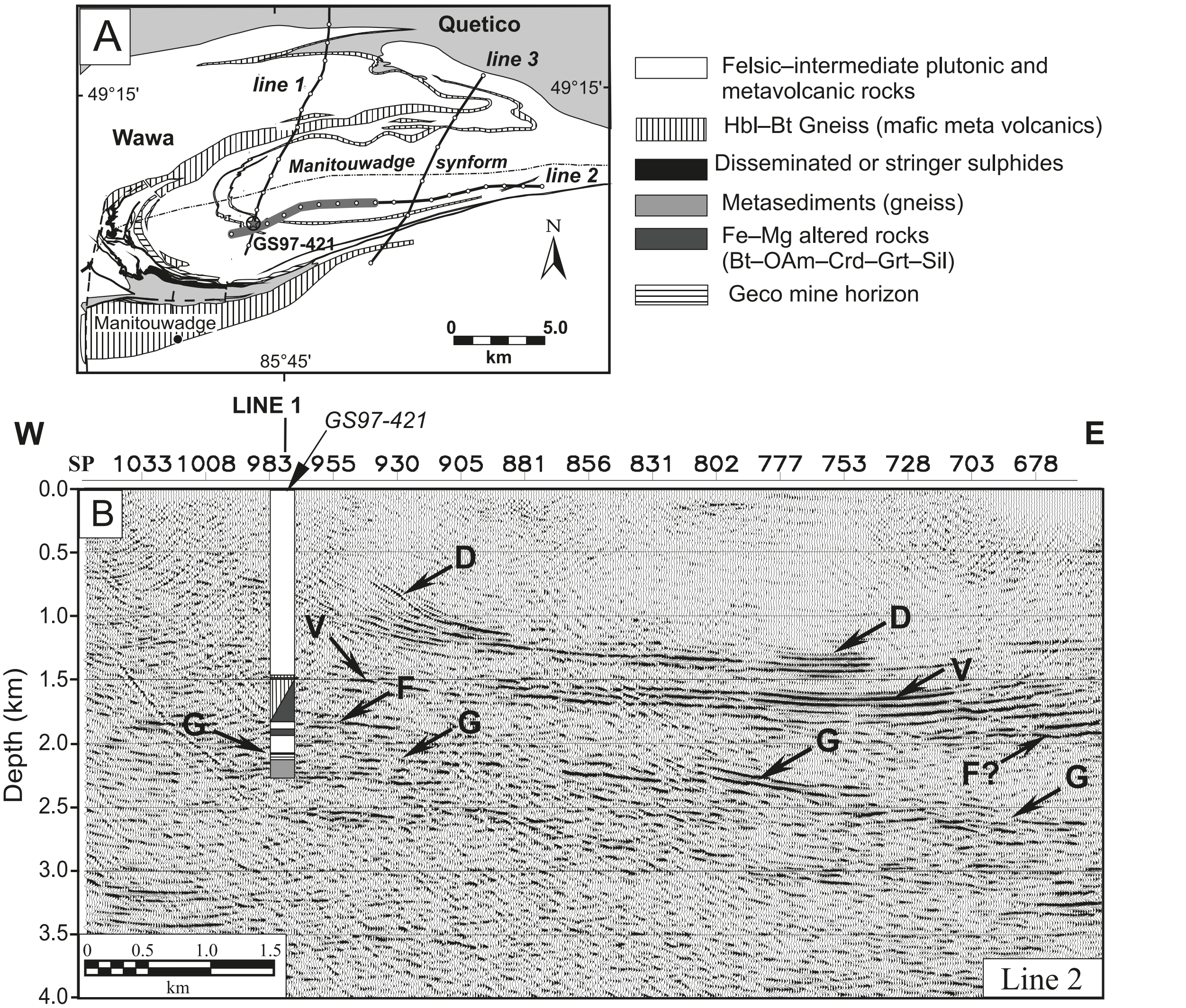
Louvicourt 3-D seismic survey, Val d'Or region

A 3-D seismic survey was acquired in 2001 to explore for deep massive sulphide deposits in the vicinity of the Louvicourt mine near Val d'Or, Quebec. The seismic data were reprocessed in 2002 and the optimum imaging offsets and azimuth have been determined (Adam et al. 2007). The seismic stacked volume shows a detailed image of the existing mine as well as a new deep and steeply dipping reflection. A followup drilling program was undertaken to verify the nature of the deep seismic anomaly, and borehole electromagnetic (BHEM) data were acquired to determine the proximity of electrical conductors that could be indicative of a massive sulphide body (Qian et al. 2004). The 3-D seismic volume provided geometrical information about deep impedance anomalies and aided in the design of an optimized drilling program. Forward modelling of the BHEM data using conductor geometries inferred from 3-D seismic data were very effective for guiding long-term exploration strategies. The combined use of surface 3-D seismic and BHEM led to the identification of an extensive zone of disseminated sulphides close to the Louvicourt mine (Fig. 17).

Discussion

Physical-property studies using borehole and laboratory data have contributed significantly to the success of Lithop-

Fig. 14. (A) Geological map of the Manitouwadge greenstone belt and Wawa–Quetico boundary region (simplified from Zaleski and Peterson 2001), showing the location of the three seismic lines and deep drill holes relevant to this study. Section of line 2 plotted in (B) has been highlighted. (B) Depth-migrated seismic section for line 2, showing lithologies from borehole GS97-421. Reflections are marked as Bt, biotite; Crd, cordierite; D, Dead Lake suite; F, mafic–felsic contact; G, Geco mine horizon; Grt, garnet; Hbl, hornblende; OAm, orthoamphibole; Sil, sillimanite; V, top of the volcanic sequence.



robe and followup studies at mining camps, since they have enabled a detailed interpretation of the origin of observed seismic signals. Base-metal deposits containing a large volume of high-impedance sulphides or oxides, such as pyrite or magnetite, meet the basic requirements (high-impedance contrast and size) to generate high-amplitude scattered signals. Although rare, direct detection of scattered signals from ore deposits is possible (Fig. 6*b*). Recognition of the scattered signals is facilitated using unmigrated 3-D seismic data, where they appear in vertical sections as diffractions and in horizontal (time) slices as approximately annular events whose radius expands with increasing two-way time.

In most cases, seismic reflections observed using high-resolution MCS profiles in mining camps are not produced directly by the ore deposits. Calibration of seismic profiles using deep drilling at mining camps indicates that, in most (but not all) cases, seismic reflections at mining camps correlate to lithologic contacts. The bimodal volcanic (mafic–felsic) environment in which VMS deposits are often located, including the Abitibi subprovince and the Manitouwadge greenstone belt, is likely to produce reflections at the contact between mafic and felsic formations. A prominent exception to this generalization is at the Buchans mine, where seismic reflections correlate mainly to regional fault structures (Thurlow et al. 1992).

Results from Lithoprobe case studies in mining camps clearly show that it is generally misleading to interpret 2-D seismic data from a hardrock environment without considering out-of-plane effects. The ideal approach is to use 3-D methods as in followup studies at Sudbury, Matagami, Half Mile Lake, and Louvicourt. In some cases, 3-D seismic is cost prohibitive, in which case the true attitude of reflections can sometimes be estimated with sufficient accuracy using out-of-plane analysis of 2-D profiles acquired along crooked lines (e.g., Bellefleur et al. 1997; O'Dowd et al. 2004). In addition, combining MCS reflection profiling with other

Fig. 15. Generalized geology of the Bathurst mining camp, New Brunswick. The Half Mile Lake deposit is located in the southwest part of the camp, as indicated by the star (modified from Bellefleur et al. 2004).

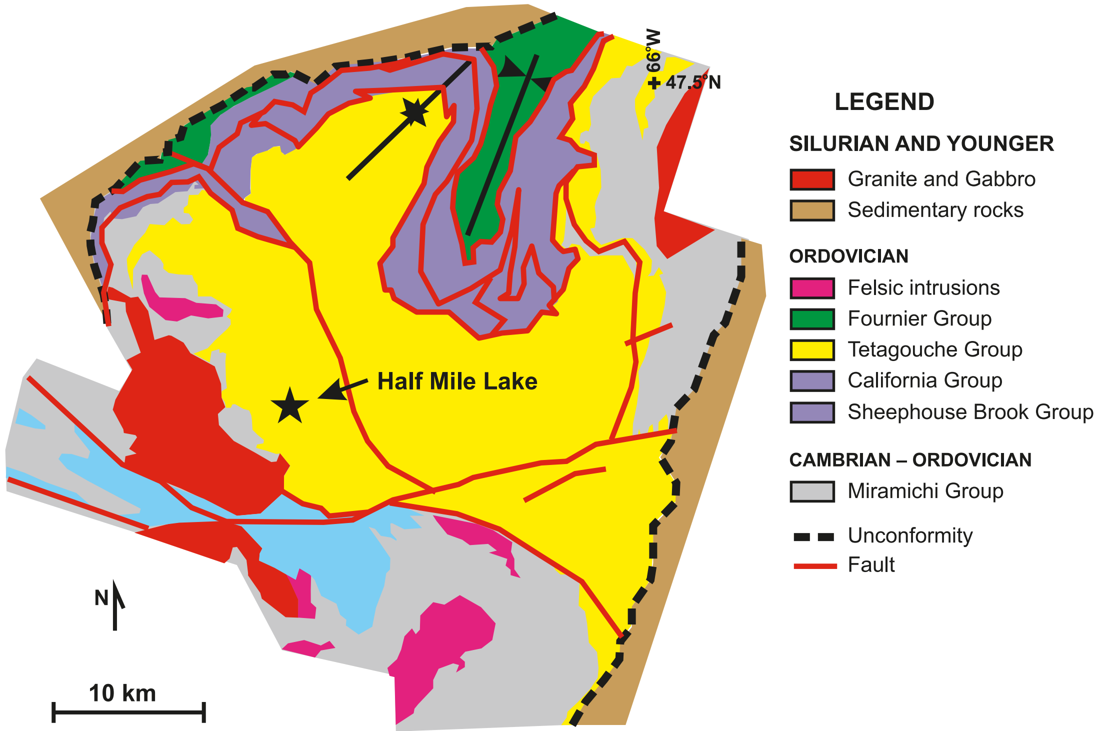


Fig. 16. Seismic cross section (no vertical exaggeration) through a 3-D multichannel seismic cube at Half Mile Lake, Bathurst camp, New Brunswick, showing images of massive sulphide deposit discovered at a depth of 1300 m by seismic reflection. Shallower deposits were known from previous mapping and drilling (after Matthews et al. 2002 and Salisbury et al. 2003).

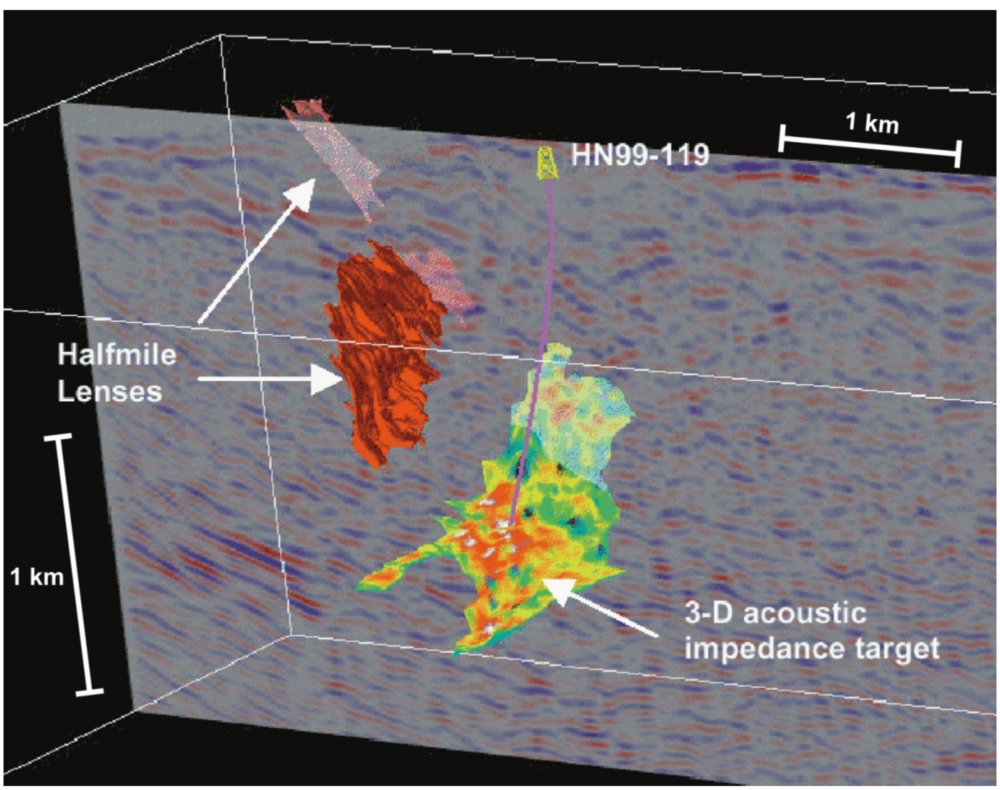
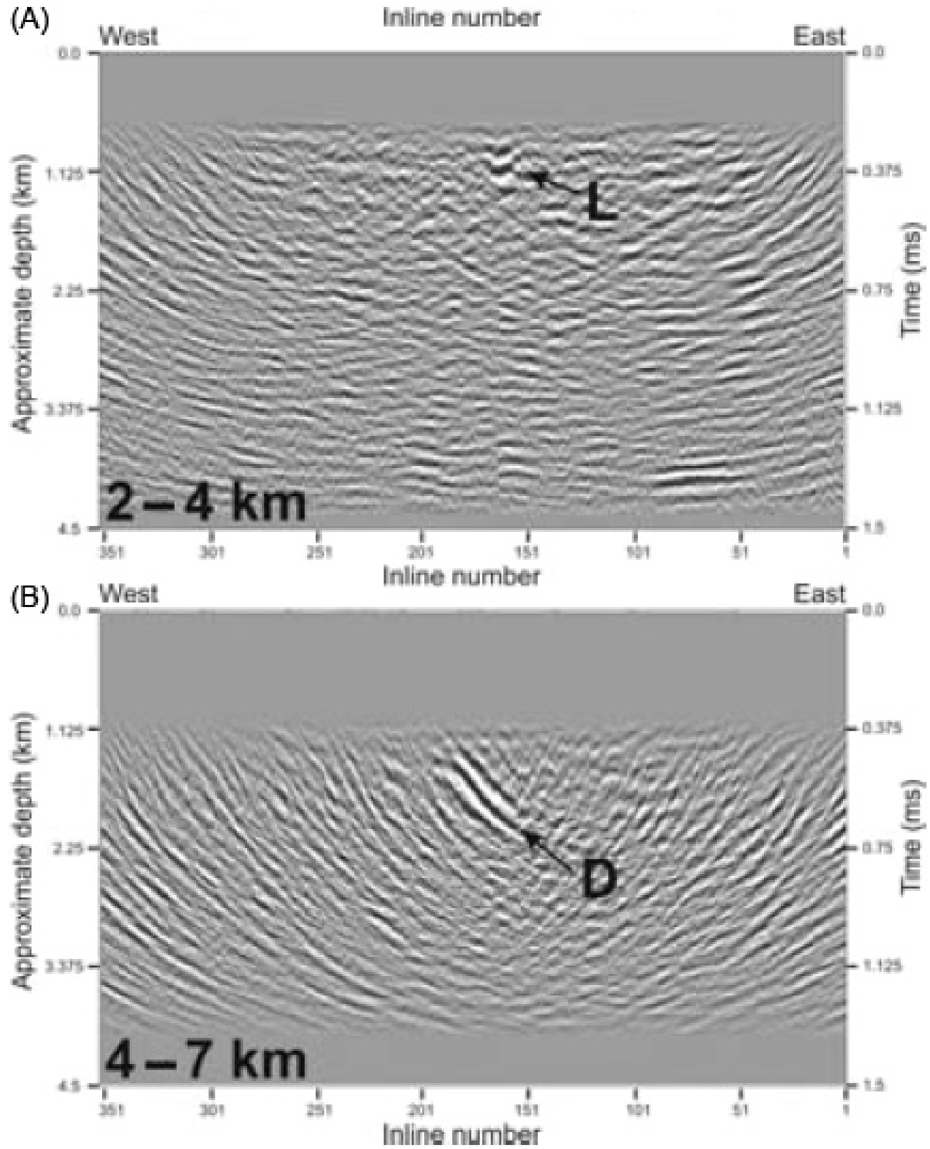


Fig. 17. Vertical section extracted from the 3-D data volume at Louvicourt, Quebec. The sections show stacked images with offset ranges of (A) 2–4 km and (B) 4–7 km, illustrating the importance of retaining large offsets while processing multichannel seismic data from a mining environment. D denotes a deeper reflection of unknown origin that is coincident with an electromagnetic anomaly; L denotes the Louvicourt orebody.



types of geophysical data, such as electromagnetic and potential-field, is an effective way to reduce uncertainty in interpretation of the seismic results.

Outside of Canada, research groups have applied techniques similar to those used by Lithoprobe. Studies in Australia (Drummond et al. 2003) have successfully applied the mineral-system concept, i.e., ore deposition requires a fluid source, a migration pathway, and a trap to provide a framework for strategic use of MCS imaging for base-metal exploration. For example, at Mount Isa, seismic imaging has been particularly effective for mapping structures that constitute favourable locations for discovery of stratabound silver–lead–zinc orebodies. In addition, alteration halos around some orebodies seem to be broad enough to form a likely target. A similar approach to identification of favourable depositional environments for base-metal deposits has been applied to buried paleokarst features along the downdip extension of massive sulphide “shoots” in northern Namibia (Stevenson et al. 2003). In the western part of the Palaeoproterozoic-bearing Skellefte District of northern Sweden, MCS profiles were acquired to image volcanic-hosted massive sulfide (VHMS) ore deposits (Tryggvason et al. 2006), following an approach very similar to Lithoprobe’s. Lastly, 3-D seismic methods have proved to be highly cost-effective for mine planning in South Africa (Pretorious et al. 2003), since they enable mapping of small-scale fault structures that affect the distribution of ores.

Conclusions

Since the initial Lithoprobe high-resolution studies in 1988, there remains considerable interest in the development of improved exploration methods to close the gap between depths at which base-metal ores can be profitably mined

(>2 km) and depths at which they can be easily detected using traditional geophysical techniques (generally <0.5 km). With this motivation, high-resolution multichannel seismic (MCS) profiles were acquired by Lithoprobe over a 5-year period in or near mining camps located in many parts of Canada. These studies were carried out as part of the Lithoprobe East, Abitibi–Grenville, and Trans-Hudson Orogen transects and have contributed toward the development of new exploration methods for deep mineral deposits in Canada. In almost every case, MCS seismic surveys in mining camps revealed coherent mappable reflections from lithologic contacts and (or) fault zones that have provided an effective framework for interpreting the geological environment of ore deposits.

Direct seismic imaging of ore deposits is challenging and rare. Seismic modelling studies confirmed by field observations show that maximum scattered-wave amplitudes are generally recorded at long offsets (>2 km) downdip of the target body. Considerable care is thus required in both survey design and data-processing steps to preserve the weak signals of interest. The use of commercial seismic contractors throughout all programs enabled Lithoprobe to take full advantage of technological improvements, such as the adoption of digital telemetry systems in the early 1990s. Case studies supported by Lithoprobe showed that the value of the seismic data is further enhanced when coincident EM or other geophysical data are incorporated into the interpretation.

In all mining camps investigated, physical rock-property studies were key to understanding observed seismic reflectivity and interpreting the profile data. These studies revealed that base-metal ore deposits have appropriate physical characteristics to produce strong seismic scattering — sulphide and oxide ores typically possess sufficient acoustic-impedance contrast with the host rocks to produce zero-offset *P*-wave reflection coefficients of 0.06 or more, considered a minimum reflection coefficient for detectability with typical signal-to-noise characteristics of Lithoprobe MCS data. In addition, deep deposits of economic interest generally meet the minimum thickness and lateral size requirements; i.e., such deposits are generally more than one quarter wavelength thick and comparable in lateral extent to the Fresnel radius. Physical-property studies undertaken as part of the Lithoprobe program underscored the importance of characterizing the seismic characteristics of key marker horizons as a necessary step towards the implementation of seismic-reflection technology for mapping the deep geology of the mining camps.

Acknowledgments

Partial funding for the mining camp seismic surveys was provided by Noranda Mining and Exploration Inc., Falconbridge Ltd., Inco Ltd., the Ministère de l'Énergie et des Ressources du Québec, and the Ontario Geological Survey. Downhole geophysical measurements were conducted by Atomic Energy of Canada, the Mineral Resources Division of the Geological Survey of Canada, and the University of Alberta. The authors also wish to recognize sustained and fundamental contributions to this field of research by Laurie Reed, Larry Matthews, and Gervais Perron. Ron Clowes is thanked for providing the base map for Fig. 1. Comments by Christopher Juhlin helped to improve the manuscript.

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