# Chapter 7
# Seismic Exploration of the Manitouwadge Greenstone Belt, Ontario: A Case History

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## ABSTRACT

The Manitouwadge greenstone belt in the Archean Superior Province of Northern Ontario, a highly deformed and metamorphosed remnant of supracrustal rocks, has been a focus of mining activity since the 1950s. However, known economic mineral deposits have been fully exhausted, providing impetus for the application of geophysical techniques that can guide further exploration for deep orebodies. A multidisciplinary approach was adopted in which the groundwork was laid for using seismic techniques to image key horizons of the major structure, the Manitouwadge synform, at depth. The use of seismic-reflection techniques as an exploration tool in crystalline rocks with a complex geological setting is unconventional. Detailed geological mapping was used to generate a working model of the subsurface geometry. This was followed by physical rock property and borehole studies, which provided the acoustic properties of the main lithological units. Three-D forward modeling using the Born approximation confirmed that, given the working geological model, reflections from the main contacts should provide a framework for the interpretation of the observed data.

A seismic program consisting of three intersecting 2D, high-resolution, reflection profiles successfully imaged several important horizons. The top of the volcanic sequence in which the known mineral deposits are hosted can be broadly imaged throughout the subsurface extent of the Manitouwadge synform, providing some guidelines for exploration. There is also an indication that the Geco mine horizon, which is host to the known mineral deposits, can be imaged with the seismic data, thus defining tighter guidelines on where further exploration is warranted. Several deep holes were drilled subsequently in order to both confirm the interpretation and investigate a number of high-amplitude anomalies observed in the seismic data. The drilling confirmed the interpretation of the main contacts imaged in the synform, but the amplitude anomalies were found to correspond to amplitude focusing artifacts along several high-impedance contacts, rather than massive sulfides as hoped. This case history demonstrates that the use of seismic-reflection technology, where appropriate and logistically feasible, can be a significant aid in mineral exploration, both for the delineation of key marker horizons and, potentially, for direct detection of massive sulfide deposits.

## INTRODUCTION

Beginning in 1995, the Geological Survey of Canada, in collaboration with Noranda Inc., undertook an integrated geophysical study of the Manitouwadge greenstone belt (MGB). The broad goals of this program were to advance our understanding of the subsurface geology of the MGB and to establish a case history to foster the technology transfer of seismic methods for mineral exploration. Three seismic profiles have been acquired across the major structure, the Manitouwadge synform (Lines 1, 2, and 3; Figure 1). Two lines (1 and 3) provide north-south profiles of the synform and they are connected by an east-west line (line 2). Although seismic line 1 extends well north into the Quetico Subprovince (Figure 1), this chapter will concentrate on the seismic data within the Manitouwadge synform, the focus of exploration activity. The northern half of line 1 has been described previously by Zaleski et al. (1997), where they correlated numerous subhorizontal and dipping reflections to reflected refractions from subvertical diabase dikes.

A number of factors in the MGB make it a favorable environment for seismic techniques aimed at regional reconnaissance and direct detection of massive sulfide bodies. The belt is host to major volcanogenic Cu-Zn deposits, including Noranda's Geco mine, which had a

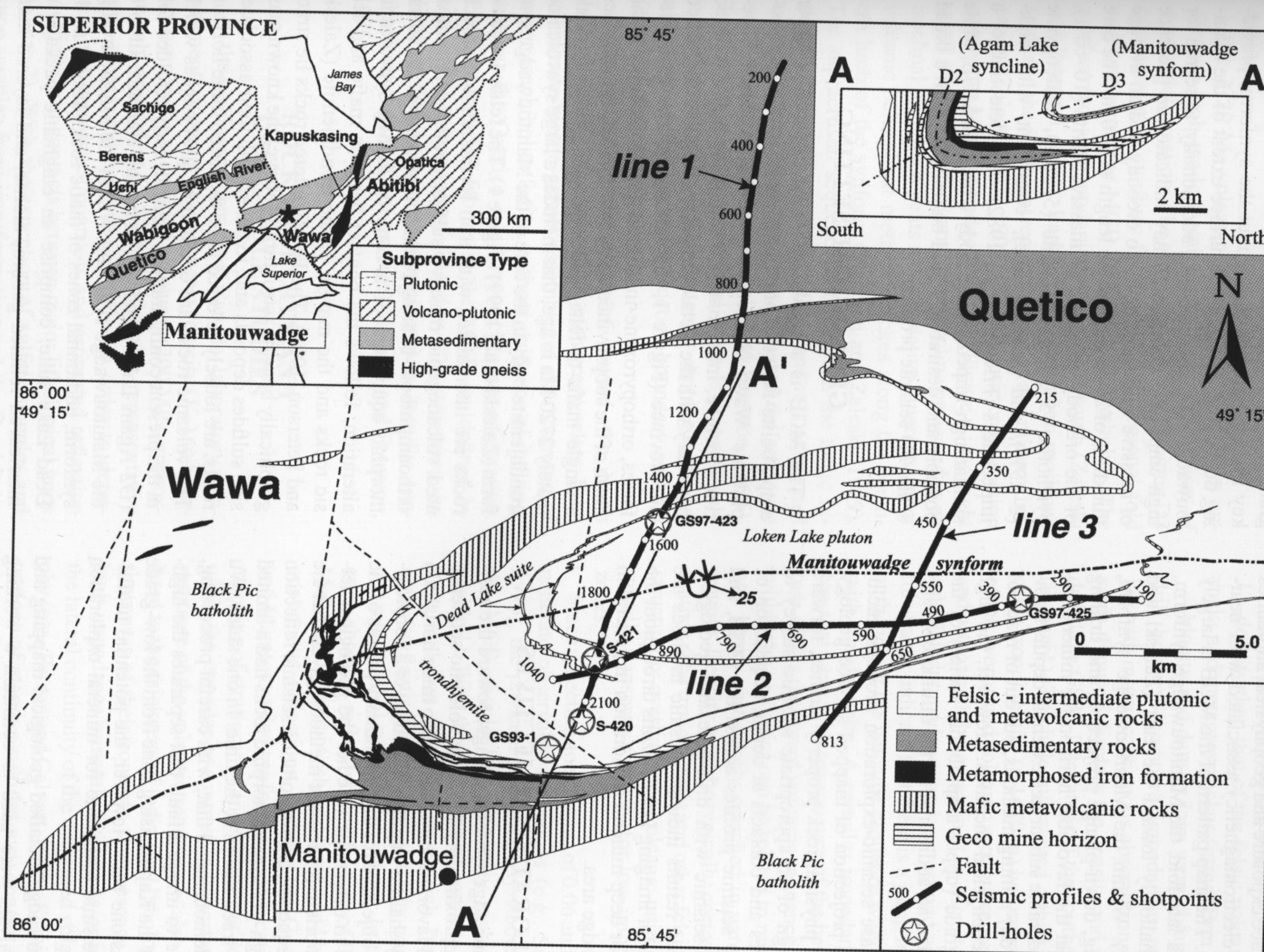


Fig. 1. Geological map of the Manitouwadge greenstone belt and Wawa-Quetico boundary region (simplified from Zaleski and Peterson, 2002) showing the location of the three seismic lines and deep drill-holes relevant to this study. The top-left inset map of the Superior Province is adapted from Card and Ciesielski (1986). The top-right inset shows a schematic cross-section across the Manitouwadge synform along the strike of seismic line 1 from work done by Peterson and Zaleski (1999).

total lifetime production of nearly 60 Mtonnes. All the known economic deposits were found in the 1950s, on the basis of surface exposure and geophysical anomalies (magnetic and electromagnetic) associated with near-surface sources. The map pattern of the MGB is largely determined by a late fold, the Manitouwadge synform, that plunges shallowly toward the east (Zaleski and Peterson, 2002). Within the Manitouwadge synform, surface mapping, down-plunge projection, and drilling data suggest that the favorable horizon for mineralization has a considerable subsurface extent at depths feasible for present-day mining methods, but out of reach of conventional geophysical methods. However, the high metamorphic grade (upper amphibolite facies) of the MGB represented an additional factor of unknown significance.

The multiphase seismic-exploration program included subsurface projection of mapped surface geology, comprehensive physical rock property studies, forward modeling, design of an appropriate seismic survey to image structures and contacts at depth, acquisition of high-frequency seismic profiles across the MGB, and integration of seismic with drill-hole and geological data. Interpreted results indicate seismic methods are a valuable tool for imaging key horizons throughout the synform and for deep mineral exploration in general in the Manitouwadge area.

## EXPLORATION OBJECTIVES

The Manitouwadge synform plunges toward the east-northeast at approximately 25°. The volcanic sequence and associated favorable horizon ("Geco mine horizon") lie at relatively shallow depths (<3 km) over a considerable area. The objectives of the preliminary phases of the program were to determine whether the geological setting was appropriate for seismic methods, given that the use of high-frequency, high-resolution seismic reflection profiling in high-grade metamorphic rocks had a limited and unproven track record at the time. In one study, Wu et al. (1992) demonstrated that, with careful processing, they were able to image a fault that separates the high-grade rocks of the Kapuskasing zone from the low-grade Abitibi greenstone belt. However, the potential usefulness of the seismic technique for mineral exploration was uncertain.

At Manitouwadge, detailed geological mapping and structural analysis were used to constrain a working model of the subsurface geometry (Zaleski and Peterson, 1995; Peterson and Zaleski, 1999) and the physical rock property, drillhole, and forward modeling results gave us confidence that key horizons should be detectable with seismic techniques. The objectives of the seismic program were to determine the subsurface areal extent of key marker horizons throughout the synform, providing depth control on the subsurface extent of the Manitouwadge volcanic rocks and, additionally, to search for high-amplitude events that may indicate the presence of massive sulfides. The Geco orebody had an average thickness of 20 m and a strike length of 740 m. The core of the orebody consisted of massive pyrite (10–60%), pyrrhotite (5–30%), sphalerite (5–30%), chalcopyrite (2–25%), and galena (trace), consistent with high-impedances (Friesen et al., 1982). The detection of a similar high-impedance orebody within the MGB, while possible and desirable, would be unlikely with a broad scale, 2D seismic program.

## GEOLOGICAL SETTING

The MGB is a highly deformed remnant of upper amphibolite-facies supracrustal rocks in the volcano-plutonic Wawa Subprovince of the Archean Superior Province, immediately south of the major tectonic boundary with the metasedimentary-migmatitic Quetico Subprovince (Figure 1, top left inset). The granulite-facies, orthopyroxene-in isograd lies immediately to the north of the subprovince boundary. The MGB comprises a single mafic-to-felsic volcanic succession, approximately 2720 Ma in age, that includes a large synvolcanic trondhjemite body in the core of the Manitouwadge synform (Zaleski et al., 1999) (Figure 1). The felsic volcanic rocks are intercalated with iron formation and associated volcanogenic massive sulfide deposits. A unit of orthoamphibole-bearing rocks, interpreted as the metamorphic equivalent of a zone of Fe-Mg synvolcanic alteration, follows the contact between mafic and felsic rocks and the margin of the trondhjemite (Zaleski and Peterson, 1995). The Fe-Mg altered rocks lie stratigraphically beneath (structurally above) the known massive sulfides deposits and, together with their associated rocks, are loosely referred to as the Geco mine horizon. The volcanic rocks are overlain by greywackes which, in the present configuration, lie in an early refolded fold (D2 Agam Lake syncline) along the southern limb of the Manitouwadge synform. Within the Manitouwadge synform, additional zones of mafic rocks known as the Dead Lake suite, comprise an enigmatic package of interleaved foliated gabbro, diorite, and layered mafic to intermediate rocks, as well as magnetite-garnet-rich rocks (Zaleski and Peterson, 1995). The MGB is enveloped by foliated multiphase dioritic to granitic rocks of the Black Pic batholith, also involved in folding. The related Loken Lake pluton is outlined by the Dead Lake suite and trondhjemite in the core of the Manitouwadge synform.

The 2720 Ma volcanic rocks of the MGB have undergone high-grade metamorphism and four phases of ductile deformation. The east-northeasterly plunging D3 Manitouwadge synform forms the major regional fold and dominates the MGB and Black Pic batholith. The axial surface dips moderately toward the south (Zaleski and Peterson, 1995). Earlier D2 deformation produced folds and the dominant regional foliation and mineral lineation (Zaleski et al., 1999). A schematic cross-section across the Manitouwadge synform (Figure 1, top right inset) shows the D2 Agam Lake syncline projected as an isoclinal fold that repeats the correlative inner and outer volcanic belts about metagreywackes along the southern limb of the synform (Peterson and Zaleski, 1999). The supracrustal sequence is thickest in the hinge region of the Manitouwadge synform and it is attenuated towards the north as strain increases and the sequence is invaded by intrusions (Zaleski and Peterson, 1995). Toward the north, the structural grain is progressively tightened and transposed into steeply dipping east-west trends typical of the Wawa-Quetico boundary and the Quetico subprovince.

Metamorphic grade increases toward the north such that the Manitouwadge metagreywackes have sillimanite-biotite-garnet assemblages characteristic of upper amphibolite facies, without evidence of melting, whereas the Quetico metagreywackes are migmatitic. The dominant D2 fabrics in the MGB are defined by high-grade minerals and folded by D3 structures, indicating that peak metamorphism was broadly synchronous with D2 deformation (Zaleski and Peterson, 1995).

## ROCK PROPERTY AND DRILL-HOLE STUDIES

At the Geological Survey of Canada, laboratory measurements of compressional wave velocity ($V_P$) and density were made at elevated pressures (200 MPa, approximately equivalent to 7-km depth) on a representative suite of ore and host rock samples in order to determine the impedance contrasts and estimated reflection coefficients at contacts between major lithological units (Figure 2). With the exception of sulfide samples and some samples from iron formation and the Dead Lake suite, we see that most points cluster along or near the Nafe-Drake curve. However, these samples define two distinct groups. The mafic-intermediate volcanics and Fe-Mg altered rocks, along with any mafic plutonic rocks occupy a region (group A in Figure 2) of distinctly higher $V_P$-density than that of the felsic volcanic and plutonic rocks and metagreywackes (group B in Figure 2).

Velocity and density logs were obtained in two deep drill holes to compare impedances measured in the lab with in-situ continuous observations at macroscopic scale. Figure 3 displays the density and velocity logs for drill-hole GS93-1, located off the southern end of line 1 (Figure 1). The hole intersected a thick unit of subvolcanic trondhjemite (~1470 m) before entering the base of the overturned volcanic section, represented by mafic and orthoamphibole-bearing (Fe-Mg altered) rocks. The calculated impedance and corresponding synthetic seismic traces indicate that there is a jump in the impedance at the top of the volcanic sequence where it is in contact with trondhjemite. A complex impedance function below that level is a consequence of the heterogeneous nature of this deformed volcanic sequence. Density spikes within the volcanics can be related to mineralized zones and layers particularly enriched in garnet and/or sillimanite. Density troughs typically correspond with pegmatites. The trondhjemite and other felsic plutonic rocks structurally overlying the volcanic units should be seismically transparent except for low-impedance fracture zones.

Since reflection coefficients of 0.06 and greater should generate observable reflections (e.g., Salisbury et al., 1996), the physical rock property studies indicate that the MGB should be moderately to highly reflective (Table 1). With the exception of contacts between mafic units and iron formation or Fe-rich Dead Lake suite rocks (reflection coefficient of 0.02), contacts between the major lithological units present in the MGB generate absolute reflection coefficients of 0.06 or greater. Mafic-felsic contacts should be marked by strong semi-continuous reflections, making the Geco mine camp and Manitouwadge synform a good location for seismic mapping of stratigraphy and structure at depth. However, while the impedance contrast is important, the seismic response of the volcanic sequence is also very much related to the thickness of individual lithological units, the sharpness of their contacts, the presence or absence of high-impedance minerals like pyrite or magnetite, and the lateral continuity of the deformed volcanic stratigraphy (e.g., Perron and Calvert, 1998). Significant concentrations of massive sulfides may appear as bright spots along mafic-felsic contacts; however, interference with the seismic response of the contact may prevent their detection.

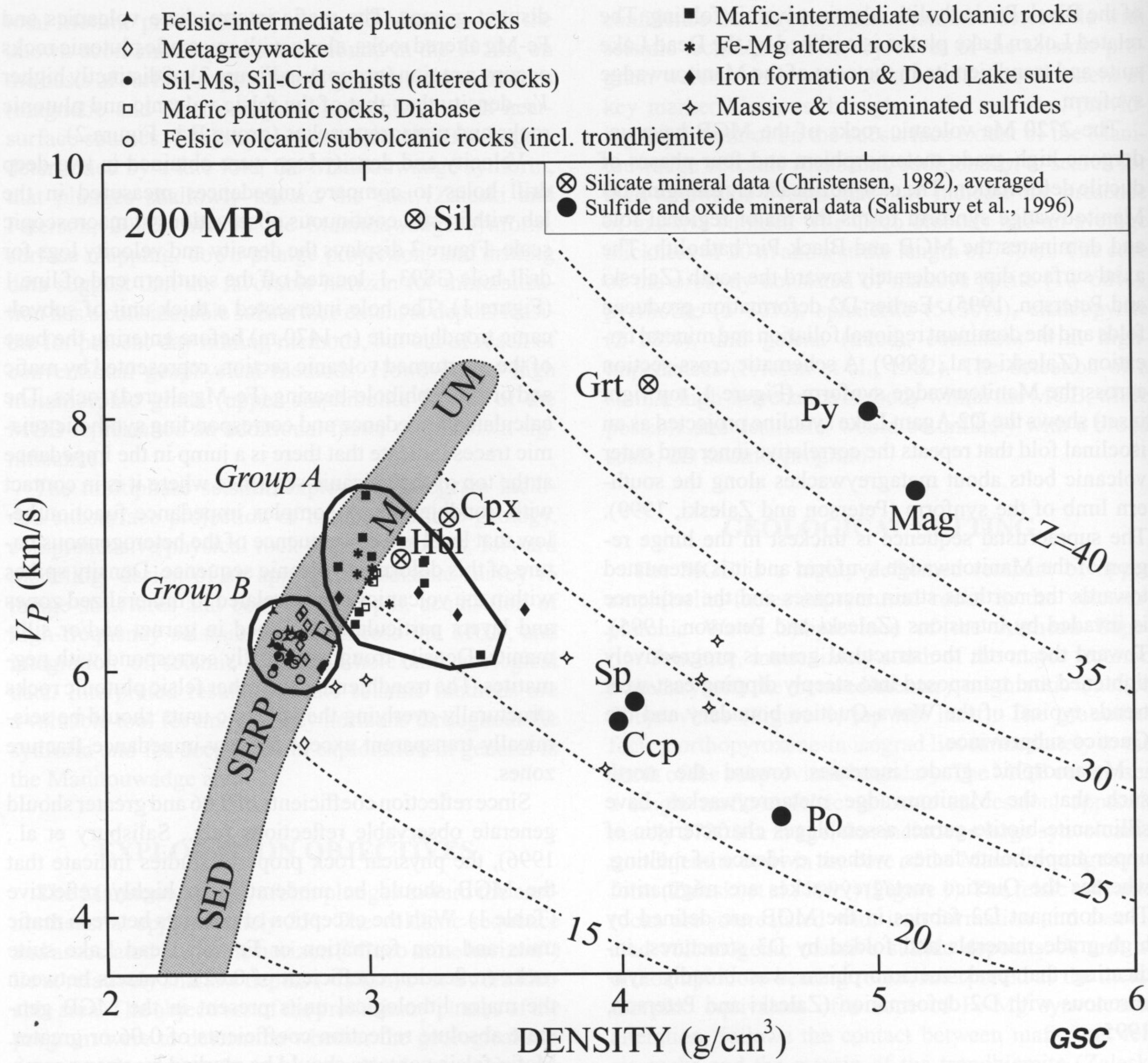


Fig. 2. Average compressional wave velocity ($V_P$) versus density for Manitouwadge samples at 200 MPa, with lines of constant acoustic impedance (Z) superimposed. Also shown are the Nafe-Drake curve for common silicate minerals and values for common silicate and pure sulfide minerals. Minerals: An—anorthite, Ccp—chalcopyrite, Hbl—hornblende, Cpx—augite, Grt—garnet (almandine-rich), Po—pyrrhotite, Mag—magnetite, Sil—silliminite, Sp—sphalerite, Py—pyrite. Silicate rocks along Nafe-Drake curve: SED—sediments, SERP—serpentinite, F—felsic, M—mafic, UM—ultramafic.

## FORWARD MODELING

In order to model the reflectivity of the MGB, synthetic seismic reflection models were generated, based on the lab measurements, logging results, and subsurface projection of the known geology. The forward modeling is important in understanding the seismic response of the various lithological contacts, and the role of the structural geometry of the Manitouwadge synform. The synthetic data constrains the geological interpretation of the observed data, rather than attempting to reproduce it. On the other hand, comparing the synthetic data with the

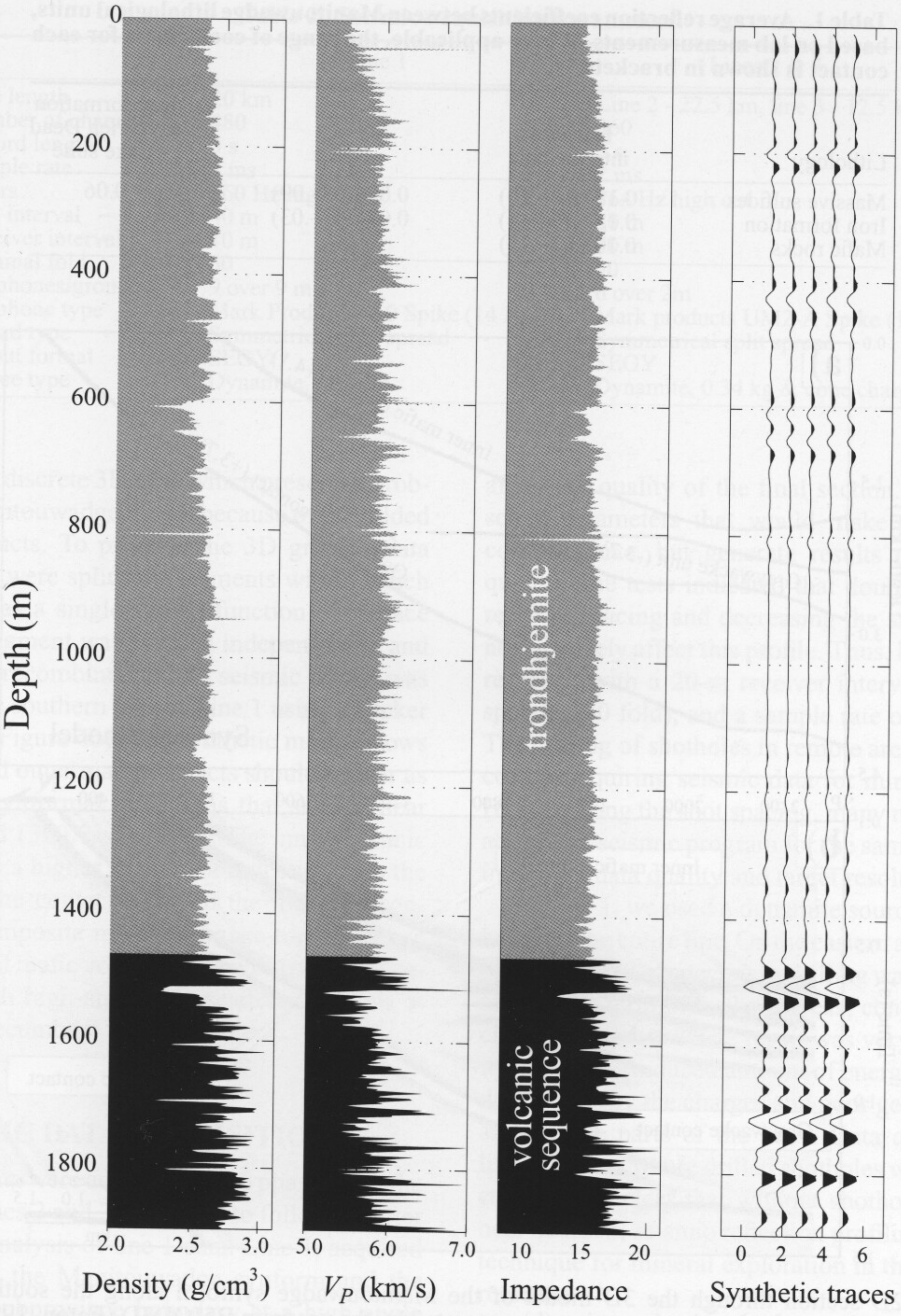


Fig. 3. Density and sonic velocity logs for drillhole GS93-1, and calculated impedances and synthetic seismogram produced using a central frequency of 50 Hz.

observed seismic data will help refine the geological model. The 3D forward modeling is also very useful for displaying the apparent dip that one can expect to observe on 2D seismic profiles—effectively, a slice through 3D structures. However, 2D seismic profiling does not image complex 3D structures properly, and there are many pitfalls associated with interpreting events that are actually reflections from contacts not in the plane of the 2D line.

For the purpose of modeling, the MGB was represented as three layers, comprising; (1) the Black Pic batholith and plutonic rocks inside the Manitouwadge

**Table 1. Average reflection coefficients between Manitouwadge lithological units, based on lab measurements. Where applicable, the range of coefficients for each contact is shown in brackets.**

| Lithology | Felsic to intermediate | Mafic | Iron formation & Fe-rich Dead Lake suite |
|---|---|---|---|
| Massive sulfides | 0.18 (.16–.20) | 0.08 (.07–.09) | 0.06 |
| Iron formation | 0.12 (.10–.14) | 0.02 (.01–.03) | – |
| Mafic rocks | 0.10 (.07–.13) | – | – |

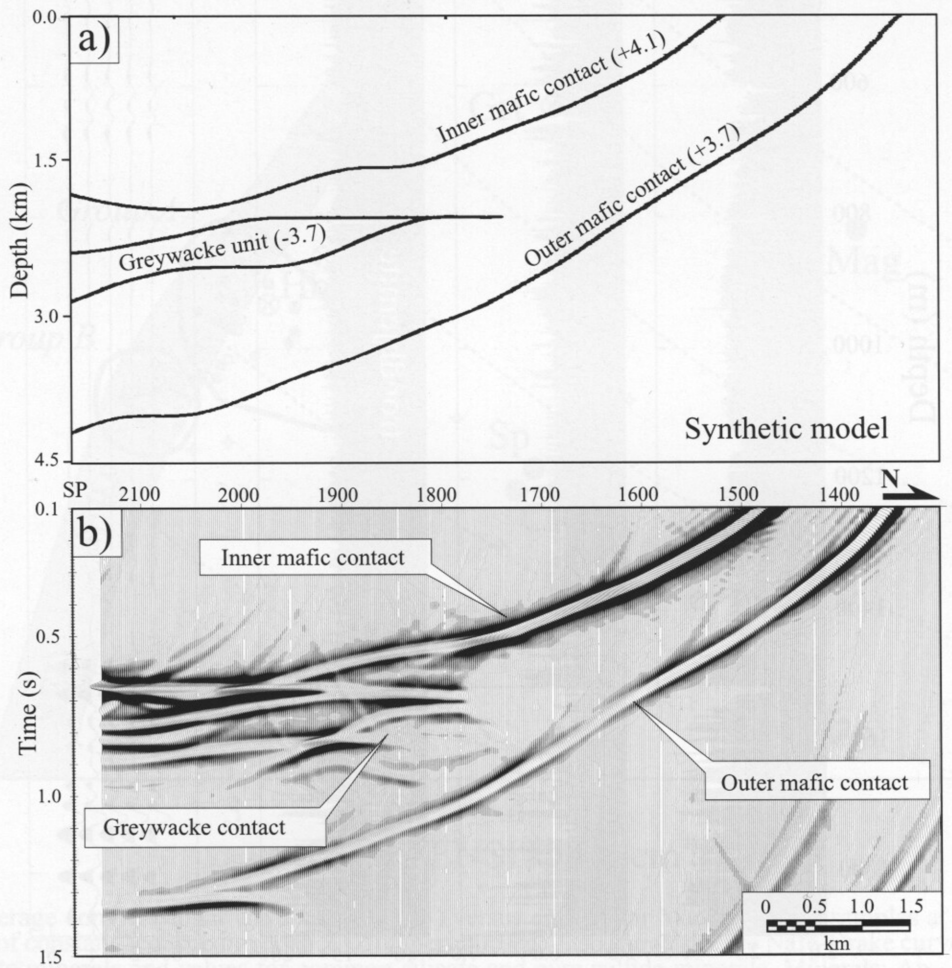


Fig. 4. A 2D section through the 3D model of the Manitouwadge synform along the southern half of line 1 (a), and the synthetic seismic section (b) generated by the program BMOD3D (Eaton, 1996) (vertical exaggeration is 1:1, assuming a velocity of 6.0 km/s). Shotpoint numbers match those for line 1 in Figure 6a. Acoustic impedance contrast (in units of gm-km-cm$^{-3}$-s$^{-1}$) is indicated for each interface.

synform (Loken Lake pluton), (2) dominantly mafic volcanic rocks (inner volcanic contact with trondhjemite and outer volcanic contact with the Black Pic batholith), and (3) greywacke, tonalite and felsic volcanic rocks but omitting interlayered iron formation (Figure 4a).

To perform the modeling, we used a Born scattering algorithm (Eaton, 1996). This approximation treats the earth as the superposition of a smoothly varying background medium and short-wavelength perturbations. The contacts of the geological model need to be

**Table 2. Seismic-acquisition parameters.**

| | Line 1 | Lines 2 & 3 |
|---|---|---|
| Line length | 20 km | Line 2 - 22.5 km, line 3 - 12.5 km |
| Number of channels | 480 | 360 |
| Record length | 3 s | 3 s |
| Sample rate | 1 ms | 2 ms |
| Filters | 160 Hz high cut | 164 Hz high cut |
| Shot interval | 40 m | 80 m |
| Receiver interval | 10 m | 20 m |
| Nominal fold | 60 | 30 |
| Geophones/group | 9 over 9 m | 6 over 2m |
| Geophone type | Mark Products L10 Spike (14 Hz) | Mark products UM2-A Spike (10 Hz) |
| Spread type | Symmetrical split spread | Symmetrical split spread |
| Output format | SEGY | SEGY |
| Source type | Dynamite, 0.34 kg | Dynamite, 0.34 kg & cone charges |

represented on a discrete 3D grid, which presented problems for the Manitouwadge model because of the folded overturned contacts. To produce the 3D gridded data set, the contacts were split into segments within which contact depth was a single-valued function of surface position, each segment was gridded independently, and the results were recombined. A 2D seismic model was generated for the southern part of Line 1 using a Ricker source wavelet (Figure 4b). The synthetic model shows that the inner and outer mafic contacts should appear as gently dipping synformal reflections that surface near stations 1480 and 1350, respectively. The inner volcanic contact produces a higher amplitude reflection then the outer contact. The contact between the metasedimentary horizon (composite metagreywacke-tonalite-felsic unit) and adjacent mafic volcanics shows up as a wedge-shaped zone with high-amplitude scattered arrivals at the nose of the recumbent fold structure.

## SEISMIC DATA ACQUISITION

The seismic data were acquired in two phases with the second phase (lines 2 and 3) designed to follow-up after processing and analysis of line 1 data. Line 1, acquired in 1995, crosses the Manitouwadge synform and the Wawa-Quetico Subprovince boundary at a high angle (Figure 1). Lines 2 and 3 were acquired in the fall of 1996. Line 2 follows the axial surface trace of the synform, and line 3 is 9-km east of line 1 and roughly parallel to it. Table 2 summarizes the acquisition parameters. Line 1 was acquired with very high-resolution parameters to maximize the potential for imaging the key horizons. Prior to the second phase of acquisition, tests were performed on line 1 data to determine how decimating the data, both spatially and in time, would affect the quality of the final section. The goal was to select parameters that would make the survey more cost effective, but generate results of similarly high quality. The tests indicated that doubling the shot and receiver spacing and decreasing the sample rate would not adversely affect this profile. Thus, lines 2 and 3 were recorded with a 20-m receiver interval, an 80-m shot spacing (30 fold), and a sample rate of 2 ms (Table 2). The drilling of shotholes in remote areas is a significant cost in acquiring seismic data for mineral exploration. By increasing the shot spacing, many more km could be added to a seismic program for the same budget without impairing data quality and target resolution.

For line 1, we used a dynamite source in drilled shotholes for the entire line. On the eastern and northern ends of lines 2 and 3, respectively, drilling was not feasible due to swampy terrain. In these areas, cone-shaped surface charges were used. The result was very poor data quality, due to the reduced amount of energy being focussed downwards by the charges and poor geophone coupling along these parts of the lines. Data quality along the line segments where drilled shotholes were used was excellent. It is clear that without shotholes drilled, in or near bedrock, seismic reflection profiling is not a viable technique for mineral exploration in the hardrock environment.

## SEISMIC DATA PROCESSING

Processing followed a conventional sequence with special attention given to some key steps which are critical to producing a high quality stacked section in crystalline rocks. The key processing steps were; (1) refraction statics, (2) coherent noise removal, (3) front mute, (4) velocity analysis, (5) dip moveout correction (DMO),

**Table 3. Processing sequence-Manitouwadge Line 1.**

| | |
|---|---|
| 1) Geometry application, first break picking and trace editing. | |
| 2) Refraction statics | - Fathom, Green Mountain Geophysics<br>- 400 m datum, 5650 m/s replacement vel |
| 3) Spectral balancing | - 35 to 165 Hz, 25 Hz window |
| 4) Front mute | - mute 35 ms after first break pick |
| 5) CDP gather | - nominal fold 60, maximum fold 115 |
| 6) NMO correction | - constant velocity, 55% stretch mute |
| ***Brute Stack*** | |
| 7) Velocity analysis | - Constant velocity stacks |
| ***Conventional Stack*** | |
| 8) Residual statics | - Surface consistent, .2 to 1.3 s window |
| 9) DMO | - Dip moveout correction using log stretch approach |
| 10) Velocity analysis | - Constant velocity stacks |
| ***DMO Stack*** | |
| 11) F-X decon | - Wiener Levinson (ProMAX) |
| 12) Migration | - Kirchhoff depth migration (ProMAX), interval velocities derived from velocity function defined above. |

**Table 4. Processing sequence-Manitouwadge Lines 2 and 3.**

| | |
|---|---|
| 1) Geometry application, first break picking and trace editing. | |
| 2) Refraction statics | - GLI3D, Hampson-Russell<br>- 340 m datum, 1 layer model, 5650 m/s replacement vel |
| 3) 2D spatial filtering | - 7 sample median filter at 3250 m/s dip (shear-wave removal) |
| 4) Air blast attenuation | |
| 5) Deconvolution | - minimum-phase spiking decon, 100 ms operator length |
| 6) Band-pass filter | - minimum-phase Ormsby band-pass, 10-30-130-150 (Hz) |
| 7) Front mute | - mute 35 ms after first break pick |
| 8) CDP gather | - nominal fold 30 |
| 9) NMO correction | - constant velocity, 70% stretch mute |
| ***Brute Stack*** | |
| 10) Velocity analysis | - Constant velocity stacks and semblance analysis |
| ***Conventional Stack*** | |
| 11) Residual statics | - maximum power autostatics |
| 12) DMO | - Ensemble DMO in T-X domain |
| 13) Velocity analysis | - Constant velocity stacks and semblance analysis |
| ***DMO Stack*** | |
| 14) Band-pass filter | - minimum-phase Ormsby band-pass, 10-30-110-120 (Hz) |
| 15) F-X decon | - Wiener Levinson, 15 traces, 500 ms window |
| 16) Migration | - Kirchhoff depth migration, max dip 60°, interval velocities derived from velocity function defined above. |

and (6) migration (Tables 3 and 4). Although processed with different software (ProMAX for lines 2 and 3, INSIGHT for line 1), the basic processing steps were similar; however, stricter quality control on the input shot gathers were required for lines 2 and 3 due to the difficult surface conditions. Processing flows were attempted that both included and completely removed the low S/N shot gathers, but, in the end, the data at the ends of lines 2 (east) and 3 (north) appear to contain no useful seismic signal.

The processing of seismic data from crystalline environments is a specialized task, and the differences from the processing strategy used by contractors for seismic data acquired in sedimentary settings for hydrocarbon exploration have been documented by a number of case histories (e.g., Wu et al., 1995; Adam et al., 1997; Perron and Calvert, 1998) and summarized nicely by Milkereit et al. (1996) and Milkereit and Eaton (1998). The differences are not so much in which steps are used, but in where one puts the emphasis to achieve the best possible results. Four such processing steps are described below.

## Refraction-Static Corrections

The Canadian Shield typically has ground conditions that vary from bedrock exposed at surface to variably thick overburden and an unpredictable depth to the water table. Seismic waves travel slowly through overburden, especially dry overburden, and are consistently fast in bedrock. Therefore, along the length of a receiver spread, a variation in the traveltimes to the receivers is typical, and is related to the thickness of the overburden layer and water table at each location. This static correction is vital in obtaining a good seismic image. Statics were calculated using the Fathom package from Green Mountain Geophysics for line 1 and GLI3D from Hampson-Russell for lines 2 and 3. Reliable first breaks are critical to a good statics solution, so the first-break picking was done very carefully by examining and tuning all the automatically generated picks. The statics solution was calculated using a single layer model with a typical overburden velocity of 1800 m/s, and a replacement velocity of 5650 m/s.

## Noise Removal

The elimination of source-generated noise is critical because in the crystalline environment we are dealing with low reflection coefficients (in the order of 5%) and,

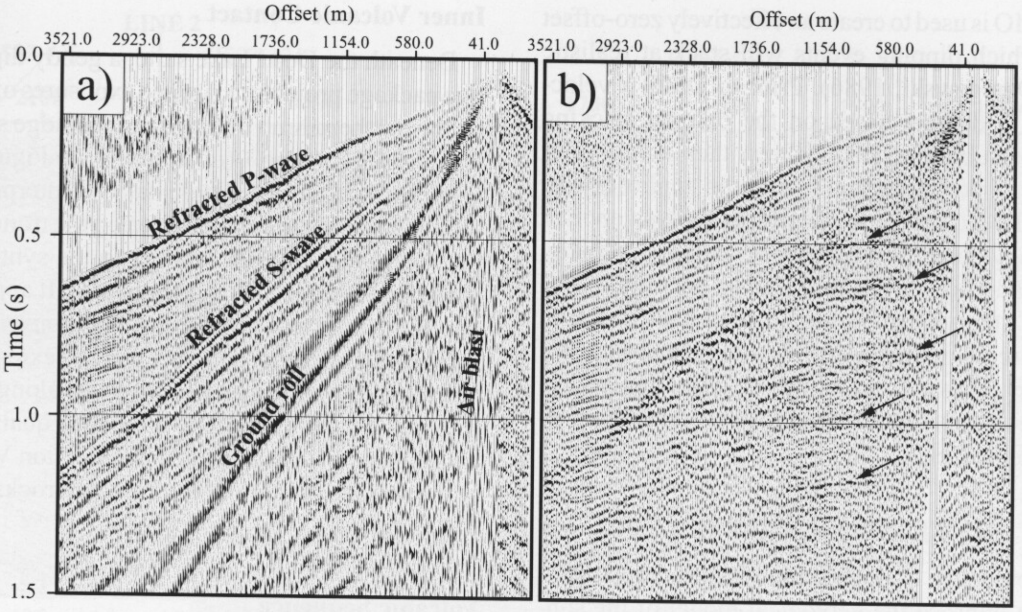


Fig. 5. Example of raw (a) and processed (b) partial shot gather (half of the receiver spread) from line 2 demonstrating the removal of various sources of coherent noise following the application of deconvolution, band-pass filtering, and windowed median filter. The arrows indicate numerous reflections on the processed gather.

thus, a low S/N ratio (Milkereit and Eaton, 1998). In a dynamite survey, the typical sources of coherent noise on the recorded shot gathers are air blast, ground roll, and shear-wave energy (Figure 5a). For line 1 we utilized spectral balancing which effectively reduced the contribution of the coherent source-generated noise and improved the temporal resolution of the data by compressing the source wavelet. A different strategy was employed with lines 2 and 3 because of unsatisfactory results with the spectral balancing available in ProMAX. Deconvolution and band-pass filtering removed most of the ground roll and dispersive energy from the shear wave, but there still remained a relatively strong, but discrete, refracted shear-wave arrival. In order to remove as much of this as possible we applied a windowed median filter which selectively removes arrivals with a specific velocity (±3450 m/s, as measured on shot gathers). Strong energy traveling at that velocity should be much reduced (Figure 5b). This process removed most of the noise, and it was anticipated that the DMO correction would attenuate the remaining coherent shear-wave energy.

## Front Mute

In high-resolution data it is particularly important to remove the first break energy (labeled refracted P-wave on Figure 5a) while retaining all the wide angle near-surface reflections that follow closely after the first break. Also, if the first break is improperly muted at far offsets, then artifacts may be introduced into the stack section well below the top 100 ms. We have used an algorithm which applies a top mute to the shot gathers from 0 s to a predefined time after the first break pick. We selected a time delay of 35 ms following the first break in order to remove just the high-amplitude part of the refracted P-wave (Figure 5a). Also important is the stretch mute that is applied following the NMO correction. After testing a full range of values on brute stacks, a stretch factor of 55% (any trace segments stretched by more than 55% are muted) was selected for line 1 and 70% for lines 2 and 3.

## DMO and Migration

At Manitouwadge the complex geological environment generates reflections with various dips. The dipping events are typically related to dipping contacts/faults or diffractions from structural discontinuities and high-impedance scatterers. In applying the normal moveout correction there is, in general, no velocity function that will simultaneously optimize stacking of both dipping and subhorizontal events. The dipping events stack at anomalously high velocities. To circumvent this problem, DMO is used to create an effectively zero-offset section in which dipping events will stack at realistic velocities (Deregowski, 1986). Prior to DMO a velocity function is defined based on the optimal stacking velocities for subhorizontal features, then a full velocity analysis is performed following the application of DMO. Finally, Kirchhoff depth migration was applied using interval velocities obtained from stacking-velocity analysis. In addition to the well known benefits of migration, this step yielded depth sections that could be compared directly with the drilling results and the geological model. However, as expected, scattering bodies within the section were too small to be well resolved by the migrated images.

## INTERPRETATION

A prime objective of the Manitouwadge seismic program was to improve the geological model of the subsurface Manitouwadge synform by broadly mapping the major horizons. Control by deep drilling is only available along the western parts and southern limb of the synform, prompted by surface mineral occurrences. In models of the 3D structure of the synform based on surface mapping, the detailed shape and depth of the synform, particularly the volcanic sequence that is known to host sulfides, was only approximated. By accurately constraining the depth to the prospective mining horizon, the seismic data have the potential to define where further exploration and drilling make economic sense. The shallow levels of the Manitouwadge synform are clearly imaged by the seismic data (Figures 6 and 7) and confirm this part of the geological model. Additionally, the small apparent dips observed along line 2 (Figure 7) provide confidence that the 2D interpretation is valid and structures are being imaged in the plane of the profile. As elaborated below, we obtained seismic images for some key geological units.

### Dead Lake Suite

Reflections from the Dead Lake suite define the gently dipping northern limb of the Manitouwadge synform (reflection D on Figure 6a). The high-amplitude reflections and lateral extent of the Dead Lake suite make it a seismic marker throughout the western part of the synform. Farther to the east, as we see in the data from lines 2 and 3, the reflections from the Dead Lake suite become weaker and semicontinuous. We interpret this change in character to layers that are becoming too thin or being disrupted by intrusions (Figures 6b and 7).

### Inner Volcanic Contact

Beneath the Dead Lake suite, a gently dipping reflective package projects to surface exposures of mafic rocks on the northern limb of the Manitouwadge synform near station 1450 on line 1 (reflection V on Figures 6 and 7). From mapping and drillhole data we interpret the top of this package as the contact between the trondhjemite and the inner volcanic belt, labeled on the synthetic section as the Inner Mafic Contact (Figure 4). It appears that the dip of the northern limb of the Manitouwadge synform is relatively uniform, since the dip and extent of this contact remains uniform as we move east along the synform (Figures 6a and b). On line 3 the data quality decreases to the north, but we suggest that reflection V may project to the surface outcrop of the volcanic rocks near station 330 (Figure 1).

### Volcanic Sequence

Once into the deformed volcanic and sedimentary package, it is apparent from the geological logs of deep drillholes that the map units defined from surface mapping will be very difficult to extrapolate across the synform using the seismic data. The metavolcanic rocks of the inner and outer volcanic belts have variable thicknesses of mafic and felsic units with considerable local heterogeneity in the volcanic stratigraphy, deformation, degree of alteration, and amount of interlayered iron formation and/or minor sulfide mineralization. Considerable lateral variation in the units can be expected. In addition to the strong reflections produced by the contacts described above, we also observe strong reflections at some of the mafic-felsic contacts within the volcanic sequence, as predicted by the rock properties. Drillhole GS97-421 is located at the intersection of lines 1 and 2, and the mafic to felsic transition at approximately 1800 m is marked by a reflection on both lines (reflection marked F in Figure 8). Also, at drillhole GS97-425 along line 2, we observe a strong reflection at 1150 m, generated at a felsic layer within mafic metavolcanic rocks (Figure 8). However, it appears that these reflections are not laterally extensive, probably due to variations in the sharpness of the mafic to felsic contact and the local thickness variations of the felsic units (reflection F on Figures 6a and 7).

### Geco Mine Horizon

Orthoamphibole-cordierite-garnet-gneiss, part of the Geco Mine horizon, lies structurally above the known mineral deposits. Surface mapping and drill data show

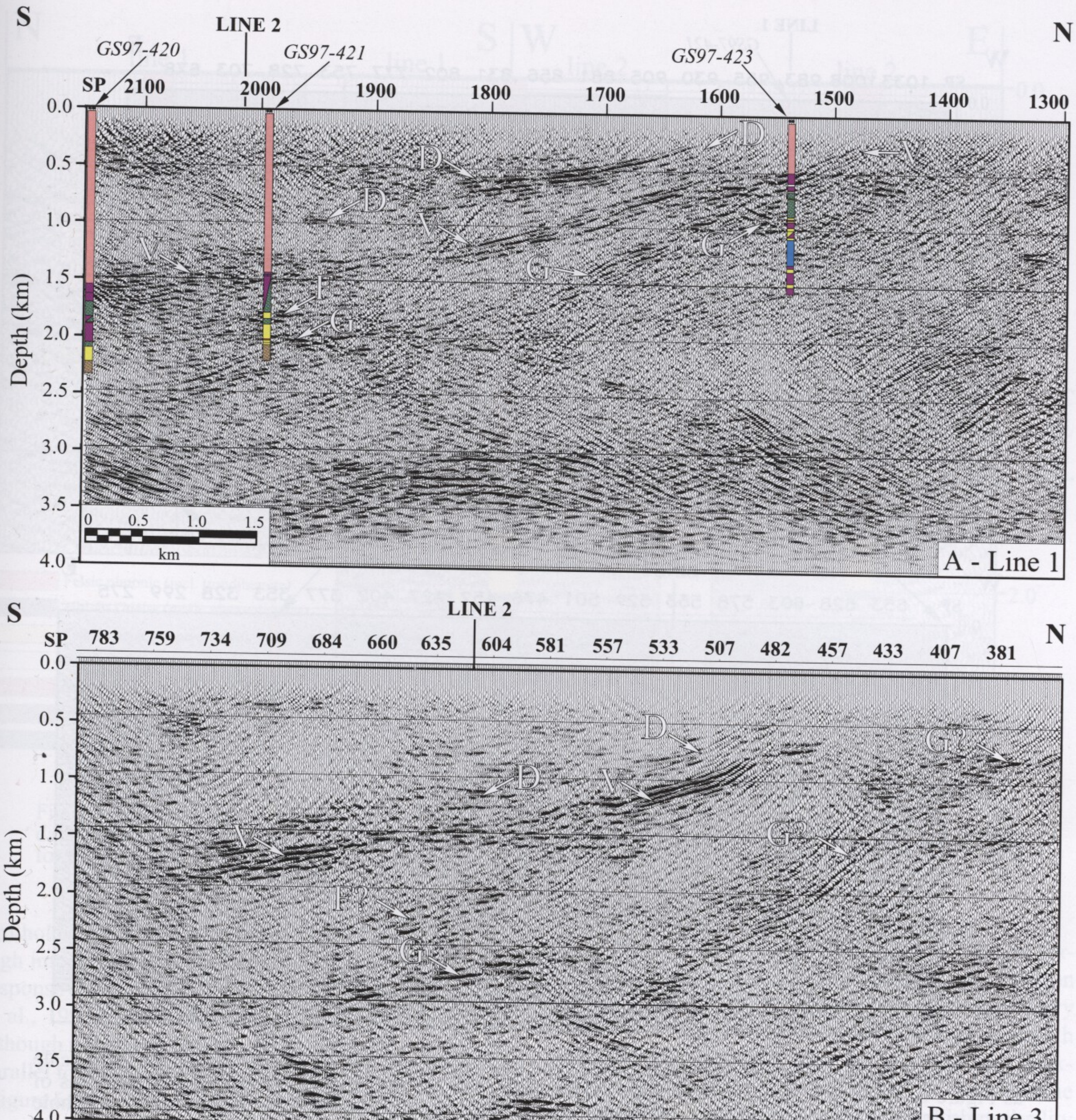


Fig. 6. Cross-sections of the Manitouwadge synform: depth migrated seismic sections for the southern half of line 1 (a) and line 3 (b). Also shown are the locations of deep drillholes and the crossline tie with east-west striking line 2. See Figure 8 for enlarged images of the drillhole lithologies and the corresponding seismic data. Reflections are marked as; D—Dead Lake suite, V—top of the volcanic sequence, F—mafic-felsic contact, G—Geco mine horizon, and are further described in the text.

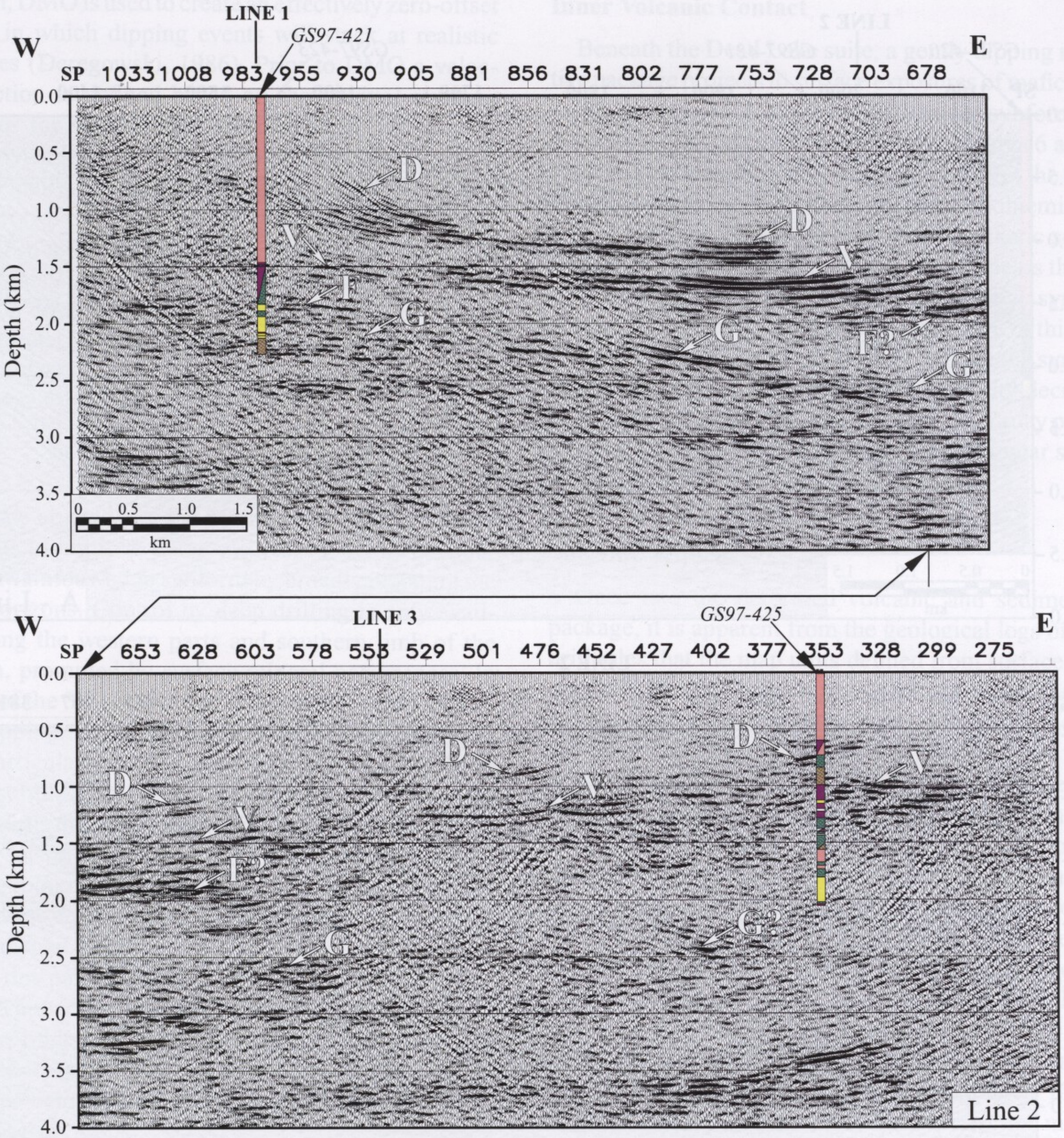


Fig. 7. Depth migrated seismic section for line 2. The line is shown in two parts, displayed at the same scale as Figure 6. The arrow indicates where the overlapping parts are joined. Also shown are the locations of deep drillholes and the intersections with lines 1 and 3. See Figure 8 for enlarged images of the drillhole lithologies and the corresponding seismic data. Reflections are marked as in Figure 6.

that this unit forms a semiconformable sheet near the stratigraphic base (overturned) of the synvolcanic trondhjemite (Zaleski and Peterson, 1995). The trondhjemite contact is a complex transition zone of septa of variably altered, mafic metavolcanic rocks and orthoamphibole-bearing, Fe-Mg altered rocks interlayered with trondhjemite at a variety of scales. Deep drillholes along line 1 (GS97-421 & GS97-423) intersected comparable rock types to the Geco mine horizon, but at variable depths, both relative to the contact with trondhjemite and within the volcanic sequence. Matching the seismic data to the geological log from drillhole GS97-421 indicates that a strong reflection is generated at or near contacts between felsic volcanic rocks and the mafic and Fe-Mg altered rocks (Figure 8). The reflectivity may be enhanced by small amounts of pyrite as encountered in

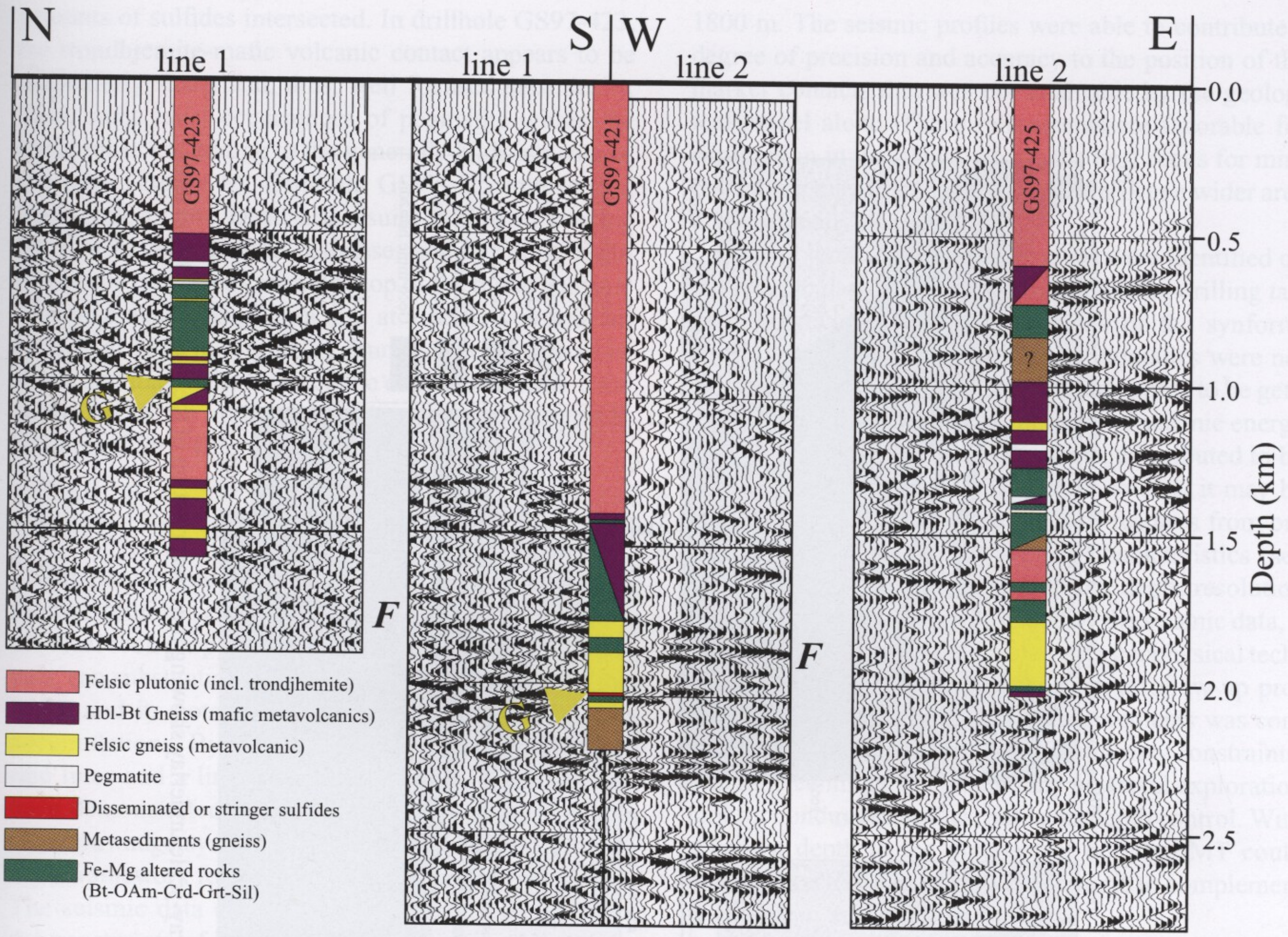


Fig. 8. Summary lithological logs for drillholes GS97-423, 421, and 425 overlain on the migrated seismic data. Lines 1 and 2 are slightly shifted with respect to each other due to the different processing datum used for each line (400 m for line 1, 330 m for line 2). G = Geco mine horizon. F = mafic-felsic contact.

drillholes GS97-421 and 423. Pyrite has an extremely high impedance (Figure 2) and can affect the reflection response even when present in small amounts (Salisbury et al., 1996). This reflection (G on Figures 6 and 7), although not always strong, can be followed along line 1 parallel to reflection V as it approaches shallower levels (Figure 6a). In drillhole GS97-423 this unit is intersected at approximately 900-m depth, so a reasonable correlation can be made between holes GS97-421 and 423 along line 1.

As we trace reflection G east along line 2 (Figure 7) it appears to increase in depth significantly and in drillhole GS97-425, it may be as deep as 2.5 km or approximately 1.5 km below the structural top (above the stratigraphic base as defined by the trondhjemite contact) of the volcanic sequence. On line 3, reflection G is also clearly observed at depth between stations 557 and 684; however, it cannot be unambiguously traced farther to the north (Figure 6b). A possible interpretation for line 3 that would be consistent with the geometry observed on line 1 is that G shallows rapidly to the north and is related to a weak south-dipping reflection package that flattens near station 381, where we observe some strong reflections prior to the region of poor data quality (Figure 6b).

### Seismic Scatterers

Drillholes GS97-423 and GS97-425 were drilled by Noranda at locations where anomalous amplitudes occurred at or near the top of the interpreted inner mafic contact. These anomalies could potentially be caused by significant amounts of disseminated or massive sulfides. However, in neither case were any significant

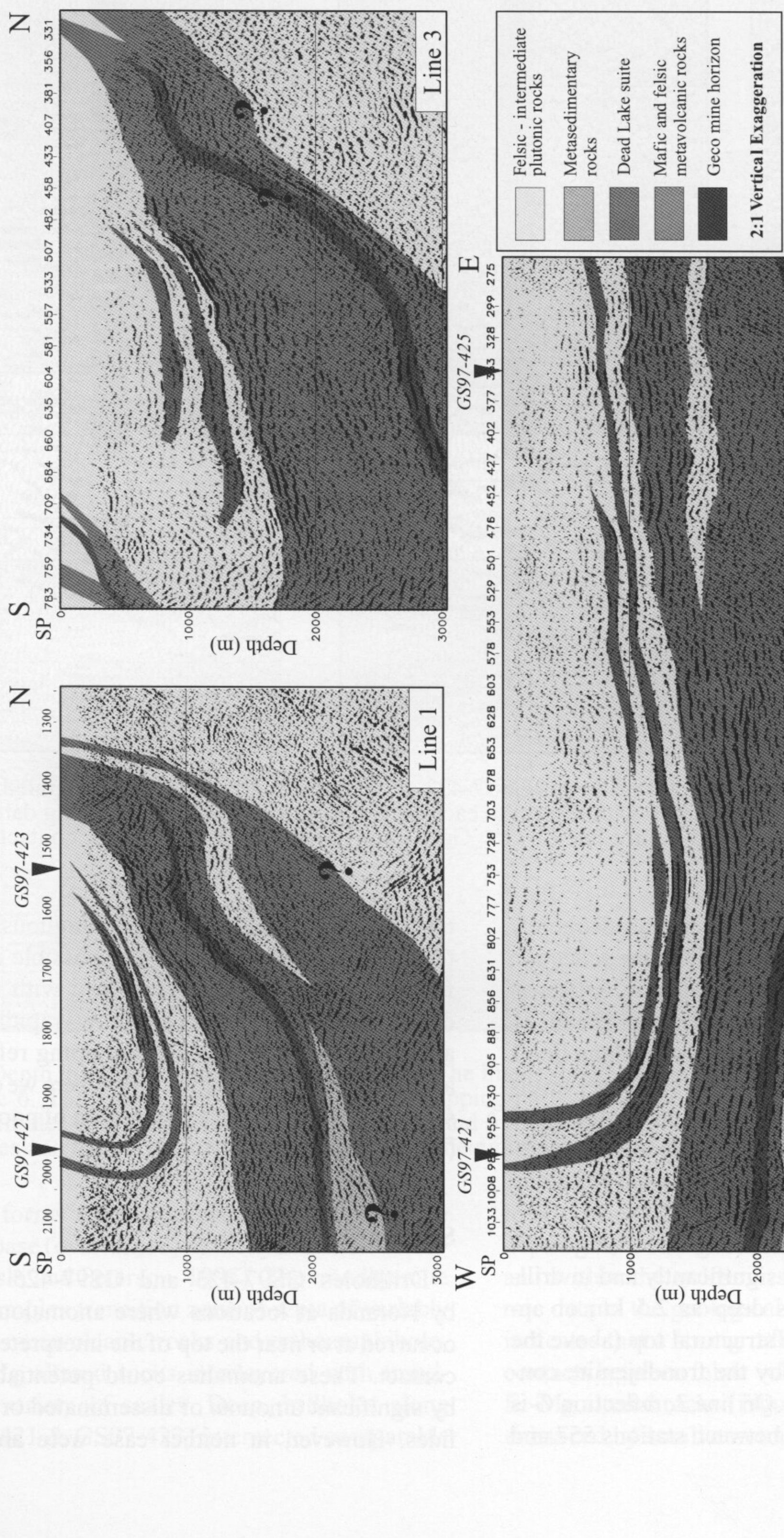


Fig. 9. Seismic lines 1, 2, and 3 (top 3 km) with a gray-scale underlay showing the interpretation of the main geological units as discussed in the text.

amounts of sulfides intersected. In drillhole GS97-423, the trondhjemite-mafic volcanic contact appears to be particularly sharp and, thus, well focused seismically. Also, some local occurrences of pegmatite within the mafic rocks are adding to the generally high-impedance contrasts (Figure 8). Drillhole GS97-425 intersects a thick zone of the Dead Lake suite at 700 m causing the first large reflection response, and the other high-amplitude reflections are at the top of the mafic volcanic sequence near 1 km depth and at a felsic volcanic interlayer at 1150 m (Figure 8). Numerous occurrences of pyrite and magnetite between the depths of 1 and 1.5 km contribute to the impedance contrasts between layers in drillhole GS97-425.

## CONCLUSIONS

Integrated studies in the MGB have shown that high-resolution seismic-reflection data, constrained by physical rock properties, modeling, and geological analysis, can substantially increase our understanding of the MGB and its potential for subsurface massive sulfide accumulations. By utilizing three intersecting 2D seismic lines and a limited number of deep drillholes, we have demonstrated that the subsurface structure of the Manitouwadge synform can be broadly imaged, providing a framework for deep mineral exploration programs. The seismic data can be effectively interpreted within the constraints of known surface geology and drillhole information to yield a coherent picture of key geological units within the synform (Figure 9). Of particular importance is the inner volcanic contact which forms a structural floor to the plutonic rocks. Since this contact defines the uppermost limit for potential mineral deposits, where it occurs at depths below which the exploitation of an ore deposit is uneconomical, no future exploration is warranted. Additionally, a package of reflectivity apparently associated with the Geco mine horizon appears to be a regional marker, and is interpreted to extend to shallow levels (<1 km depth) near much of the north limb of the synform. However, the horizon appears to deepen significantly to the east along line 2 (Figure 9).

Interpretation of the seismic data has refined the geological model for the Manitouwadge synform. The shallowing of the prospective horizon to the north previously was not well constrained from surface geology, and the depth to the contact between trondhjemite and the inner volcanic belt at the deepest part of the synform is now estimated to be 1300 m, whereas the model had predicted 1800 m. The seismic profiles were able to contribute a degree of precision and accuracy to the position of the marker contacts that was not attainable by the geological model alone. These refinements are favorable for exploration in that they indicate the host rocks for mineralization may lie at accessible depths over a wider area than originally predicted.

Several local amplitude anomalies were identified on the seismic data which provided interesting drilling targets in previously unknown regions of the synform. Unfortunately, where drilled, these anomalies were not related to massive sulfides, but instead appear to be generated by particularly strong focusing of seismic energy along some high-impedance contacts, contributed to by reflective pegmatite layers. In future studies, it may be possible to distinguish these types of features from ore deposits on the basis of scattering characteristics (see Bohlen et al., this volume). With the depth resolution and structural framework provided by the seismic data, it may have been possible to utilize other geophysical techniques to scan for anomalies. In fact, a follow-up program of magnetotelluric (MT) measurements was considered but not completed due to budgetary constraints. The MT technique is a potentially powerful exploration tool for conductive bodies, but lacks depth control. With a known depth to the prospective horizon, MT could have proven to be an effective technique to complement results from the seismic program.

If a strategic seismic program was to be attempted at Manitouwadge for mineral exploration, 3D seismic methods should be considered in order to better image the detailed structures in their true orientation and, potentially, to directly detect massive sulfides. The challenges of acquiring high-quality seismic data in crystalline rock terranes are significant, however, and the technique cannot be used as an exploration tool in all environments. A careful step-wise approach, as was performed in this study, is recommended to maximize the chances of success.

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