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Seismic-reflection data from the Sturgeon Lake mining camp, northern Ontario

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Roberts, B. and Adam, E., 1999: Reflection seismic data from the Sturgeon Lake mining camp, northern Ontario; in *Current Research 1999-E; Geological Survey of Canada, p. 00–00.*

Abstract: In November 1997, Noranda Mining and Exploration Inc. acquired a 7.8 km seismic line in the vicinity of the Sturgeon Lake mining camp in Northwestern Ontario. The data processing was done by the Geological Survey of Canada and the results are presented in this report. Recent studies have shown that the seismic-reflection technique can be an important tool in mineral exploration if certain geological criteria are met, and the data are carefully processed. The main focuses in the processing were noise elimination, static corrections, and determination of the correct velocity field. We also tested prestack migration by utilizing an equivalent-offset technique. This method provided an alternative final section which aided in the data interpretation. The dynamite data displayed high signal levels and we observed strong reflectivity at depth. However, the near-surface reflectivity is weak, likely due to the complexity and steepness of the geological structures.

Résumé : En novembre 1997, un profil sismique d'une longueur de 7,8 km a été collecté dans la région du camp minier de Sturgeon Lake, situé dans le nord-ouest de l'Ontario, par Mines et Exploration Noranda Inc. La Commission géologique du Canada a été choisie pour le traitement des données, et les résultats sont présentés dans ce rapport. Des études récentes démontrent que la méthode de sismique-réflexion peut être utile à l'exploration minérale lorsque certains critères géologiques sont rencontrés et que les données sont traitées adéquatement. Lors du traitement des données, une attention particulière a été accordée à l'élimination du bruit, aux corrections statiques et à la détermination des vitesses sismiques. La migration avant-sommation a aussi été testée en utilisant la méthode des séparations équivalentes. Cette méthode procure une section somme finale pouvant aider l'interprétation des données. La source de dynamite a généré des arrivées d'amplitudes élevées et on observe de fortes réflexions en profondeur. Toutefois, il y a peu de réflexions proches de la surface, ce qui est probablement dû à la complexité et à la pente abrupte des structures géologiques.

INTRODUCTION

There are an increasing number of studies which demonstrate the benefits of using the seismic technique in existing mining camps. In particular, they show that it is a cost-effective way to map favourable mine horizons (e.g. Milkereit et al., 1996; Perron et al., 1997), and is potentially capable of directly detecting massive sulphide deposits (e.g. Adam et al., 1997). It has been shown that the success of seismic studies in a crystalline environment is dependent on prior knowledge of the structures (i.e. dip, strike, thickness) and the physical properties (i.e. density and velocity) of the host rocks and mineralization. This information is obtained by geophysical logging in existing boreholes, performing lab measurements on rock samples, and examining the geological database.

In November 1997, Noranda Mining and Exploration Inc. took the opportunity to utilize a seismic crew that had been mobilized from Calgary for the acquisition of the LITHOPROBE Western Superior seismic transect to acquire a 7.8 km seismic line near several existing mining camps in the Sturgeon Lake greenstone belt, Northern Ontario (Fig. 1). The area is well mapped, and Noranda has a number of boreholes in the vicinity of the seismic line to aid in the interpretation of the data.

Processing of the seismic data was undertaken at the Seismology and Electromagnetism Section of the Geological Survey of Canada using the ProMAX seismic data-processing software. Detailed geological information on the study area was not available, and, as a result, this report outlines the processing performed and displays the final sections along with a description of the main features in the data, rather than providing a complete interpretation of the data.

GEOLOGICAL SETTING

The Sturgeon Lake greenstone belt lies in the Superior Province at the boundary between the central and western Wabigoon Subprovince where Mesoarchean crust (central Wabigoon) appears to lie adjacent to younger supracrustal belts (western Wabigoon) (Thurston et al., 1991). Greenstone belts (ca. 2.73 Ga) are widespread in the Wabigoon Subprovince and host numerous base-metal occurrences. The

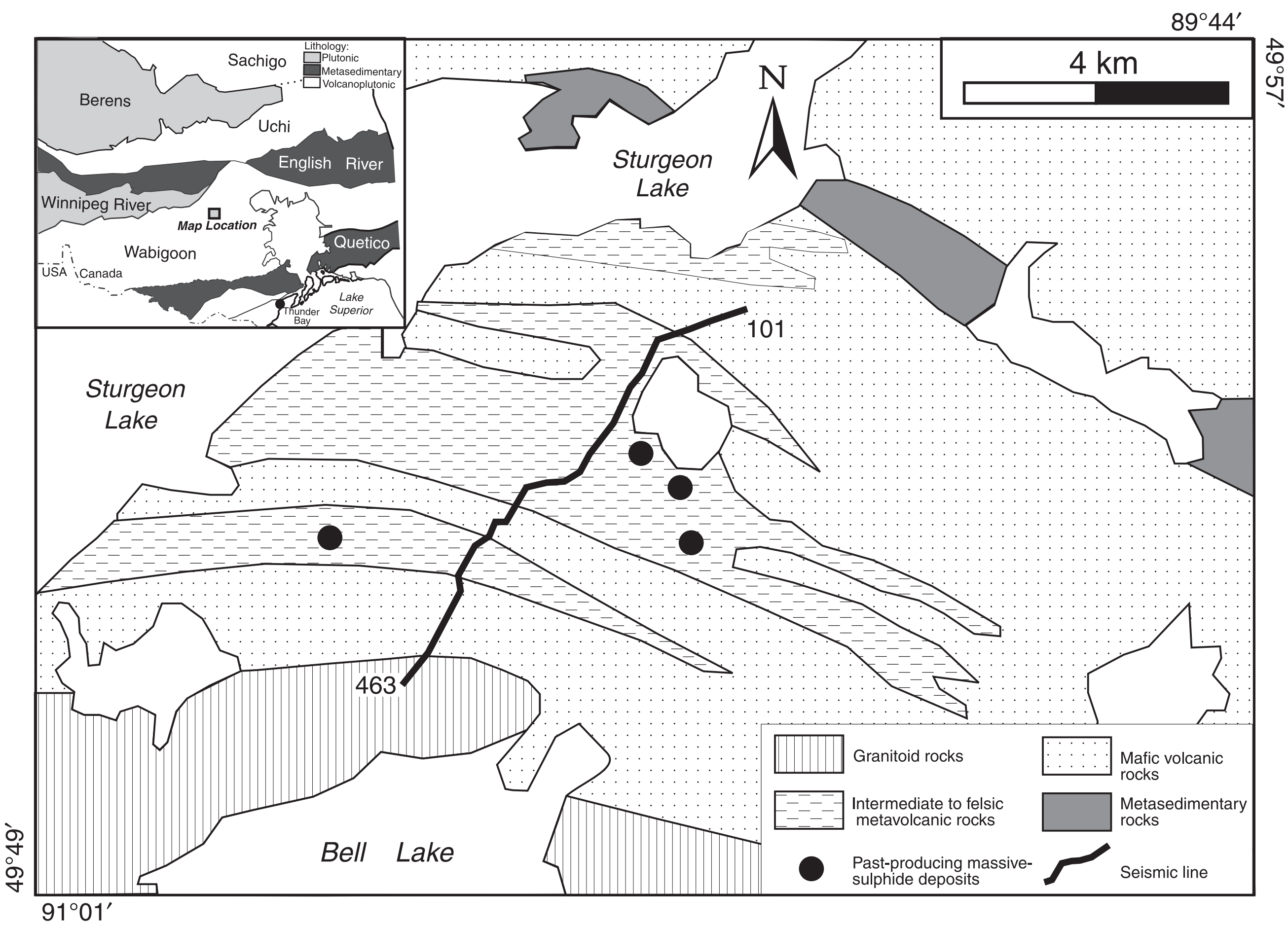

__Figure 1.__ Map showing the location of Sturgeon Lake seismic line 1 and the regional setting of the Sturgeon Lake mine camp area within the Archean Superior Province (inset). Geology is modified from Sanborn-Barrie et al. (1998).

area of interest for this study has been mapped in detail, and the zone which contains the known mineral occurrences has been interpreted as an Archean submarine caldera complex (Morton et al., 1991). The caldera volcanic rocks overlie a pre-caldera volcanic cycle to the south, and are overlain by younger mafic volcanic rocks to the north (Fig. 1). All the metavolcanic units in the Sturgeon Lake mine-camp area are dated in the 2.70–2.735 Ga range.

SEISMIC-DATA ACQUISITION PARAMETERS

Receivers along the entire seismic line were active for all the shots, and 3 s of 393-channel data were recorded with a sampling rate of 1 ms for each of the 223 dynamite shots. The 393 trace spread used a receiver spacing of 20 m and the shot spacing was 40 m. A visual inspection of the shot gathers indicated that the dynamite shots provided ample source energy with strong first-break energy along the entire spread of receivers and obvious reflection energy is seen at 1.5 and 2.5 s.

DATA PROCESSING

The processing of seismic data can be divided into those steps which are performed prior to stacking the seismic traces (referred to as prestack) and those done after stack (or poststack).

Prestack

The prestack processing of the shot gathers focuses mainly on the elimination of noise (both source generated and ambient background), the application of static corrections, and the determination of the correct velocity function for stacking the data (including the application of dip-moveout correction). Noise elimination is critical, because in the crystalline environment we are dealing with low-reflection coefficients and thus, a low signal-to-noise ratio. Below we have listed the highlights of the prestack processing with applicable comments.

Geometry definition

The seismic line was not straight (Fig. 1); however, a smooth binning line could be fitted through the source-receiver midpoints such that most of the common-depth-point (CDP) bins contain a full range of offsets. The CDP fold is as high as 224 in the middle of the line, smoothly tapering to a low fold at the ends of the line. Elevations vary by only 10 m along the length of the line.

True amplitude recovery

To correct for amplitude loss due to spherical divergence, the data were scaled using a time-variant factor [1/(time•velocity^2)] with a constant velocity of 6000 m/s. As well, a full-trace (3 s) automatic-gain function was applied to all traces in order to correct for variations in source and receiver coupling.

Deconvolution

Deconvolution improves the temporal resolution of seismic data by compressing the seismic wavelet. After testing, a minimum-phase spiking deconvolution was performed using an operator length of 120 ms.

Bandpass filter

The low-frequency end of the spectrum primarily contains the dispersive ground-roll energy and air blast (*see* Fig. 2a) along with ambient noise related to workings at the mine site, small streams, etc. To remove this energy, the low cut of the bandpass filter was set at 32 Hz. The shot gathers also contain abundant high-frequency energy, beyond 200 Hz, but it was observed that the reflective energy in the shot gathers was below 150 Hz. The bandpass filter was thus set to be quite wide, between 32 and 150 Hz, at this early stage of the processing.

Elevation statics

The data are corrected to a flat datum of 430 m using a replacement velocity of 5900 m/s.

2-D spatial filtering

After deconvolution and bandpass filtering, there still remains a relatively strong, but discrete, refracted shear-wave arrival (head wave) (Fig. 2a). In order to remove as much of this as possible, we applied a median filter which is focused along a specific velocity (± 3450 m/s in this case). Strong energy travelling at that velocity should be much reduced. This process was about 80% effective, but it was anticipated that the dip moveout (DMO) correction would attenuate the remaining coherent shear-wave energy.

Mute first-break energy

Trace muting is based on the first-break picks. The data is muted from 30 ms below the first-break pick to the top (time 0).

Figure 2b displays the top 1 s of a processed shot gather at this point of the processing sequence. The coherent noise has been effectively removed and the reflectivity, although weak, can now be identified.

Refraction-statics application

The Canadian shield typically has ground conditions that vary from bedrock at surface to variably thick overburden and an unpredictable height for the water table. Seismic waves travel slowly through overburden, especially if it is dry, and are consistently fast in bedrock. Therefore, along the length of a receiver spread, a variation in the traveltimes to the receivers is normally observed that is related to the thickness of the weathering layer at each location. This static correction is vital in obtaining a good seismic image in any mining-camp-scale seismic survey. In this case, a one-layer refraction-statics model was defined using the uphole times from the shots and the ProMAX refraction-statics package. Three methods were used for the computations (diminishing residual matrices (DRM), generalized residual method (GRM), and delay times) and all came up with comparable results. The depth-of-overburden model and the source and receiver statics used to correct for the weathering layer are shown in Figure 3.

Residual statics

The lateral continuity of reflection energy can be improved prior to the stacking process by calculating source and receiver statics which yield a maximum CDP-stack power over a given window on each CDP gather. This process can be effective in low signal-to-noise data. Surface consistent residual statics were calculated using a 600 ms window centred on the strong package of reflectivity at approximately 1 s.

Dip moveout correction (DMO)

In complex geological environments, reflections with various dips are commonly observed and this is true at Sturgeon Lake. The dipping events are typically related to steeply dipping contacts, faults, or diffractions from structural discontinuities and high-impedance scatterers. In applying the normal moveout correction there is no velocity function that will simultaneously optimize stacking of both dipping and

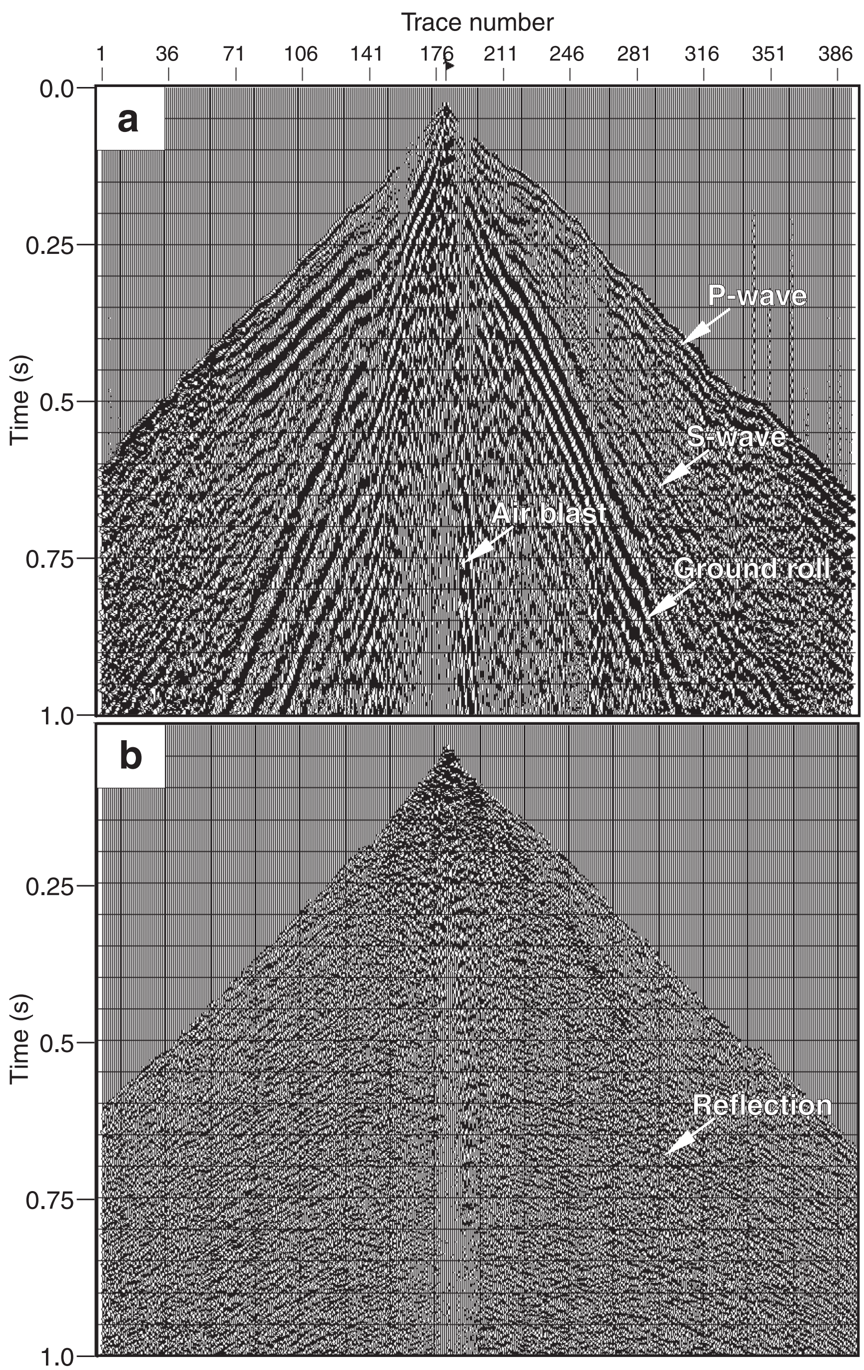

Figure 2.

*A display of the top 1 s of a raw (**a**) and processed (**b**) shot gather from station 255 on line 1 The weak reflectivity is apparent on b after the removal of all the coherent noise.*

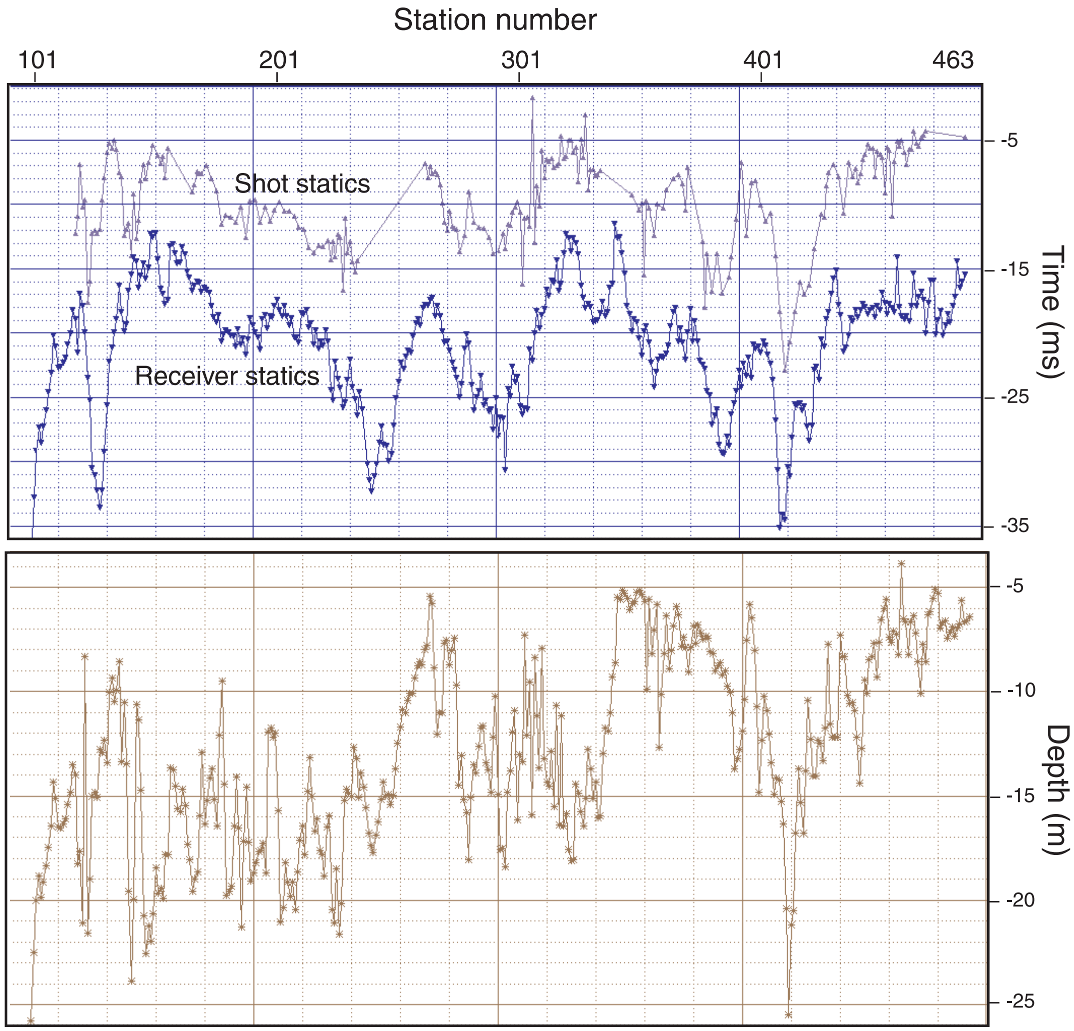

Figure 3. *Shot and receiver refraction statics (top) and depth of overburden (bottom).*

subhorizontal events. The dipping events stack at anomalously high velocities. To circumvent this problem, DMO is used to effectively create a zero-offset section, in which dipping events will stack at realistic velocities. Prior to DMO, an average background velocity (6000 m/s) is used to correct the data, then a full velocity analysis is performed following DMO.

Velocity analysis

The velocity analysis was performed using a combined semblance/constant-velocity stack display every 50 CDPs (500 m). The velocities varied somewhat along the line, but on average the velocity function varies from 5600 m/s at the surface to 6350 m/s at depth (*see* Table 1).

Table 1. Typical velocity function used for NMO correction of Sturgeon Lake line 1.

Time (ms)	RMS Velocity (m/s)
50.0	5600
300.0	5900
500.0	6000
1000.0	6100
2400.0	6350

Normal moveout (NMO) correction and CDP stack

Following the NMO correction, the data are stacked using a straight mean stack with a maximum fold of 224.

Poststack

Bandpass filter

Up to this point we have maintained a wide frequency spectrum in the data. This is to ensure that every chance is given to enhance the high-frequency data, especially in the top 0.5 s. In analyzing the data poststack, it is observed that most of the coherent energy lies in the 30–80 Hz range, with some higher frequency signals (up to 120 Hz) in the upper part of the section. Because of this, a time-variant bandpass filter was applied at this point (0–0.3 s, 30–120 Hz; 0.3–0.45 s, 30–100 Hz; 0.45–3.0 s, 30–80 Hz).

F-K migration

Stolt F-K migration with a constant velocity of 6000 m/s (average background velocity) was applied.

Automatic gain control (AGC)

A scale factor is calculated using a 1 s window and applied to the sample at the centre of the window.

OBSERVATIONS FROM THE STACKED AND MIGRATED SECTIONS

The data acquired at Sturgeon Lake are of high quality and the data processing was fairly routine with no major problems encountered. The geological information required to do a

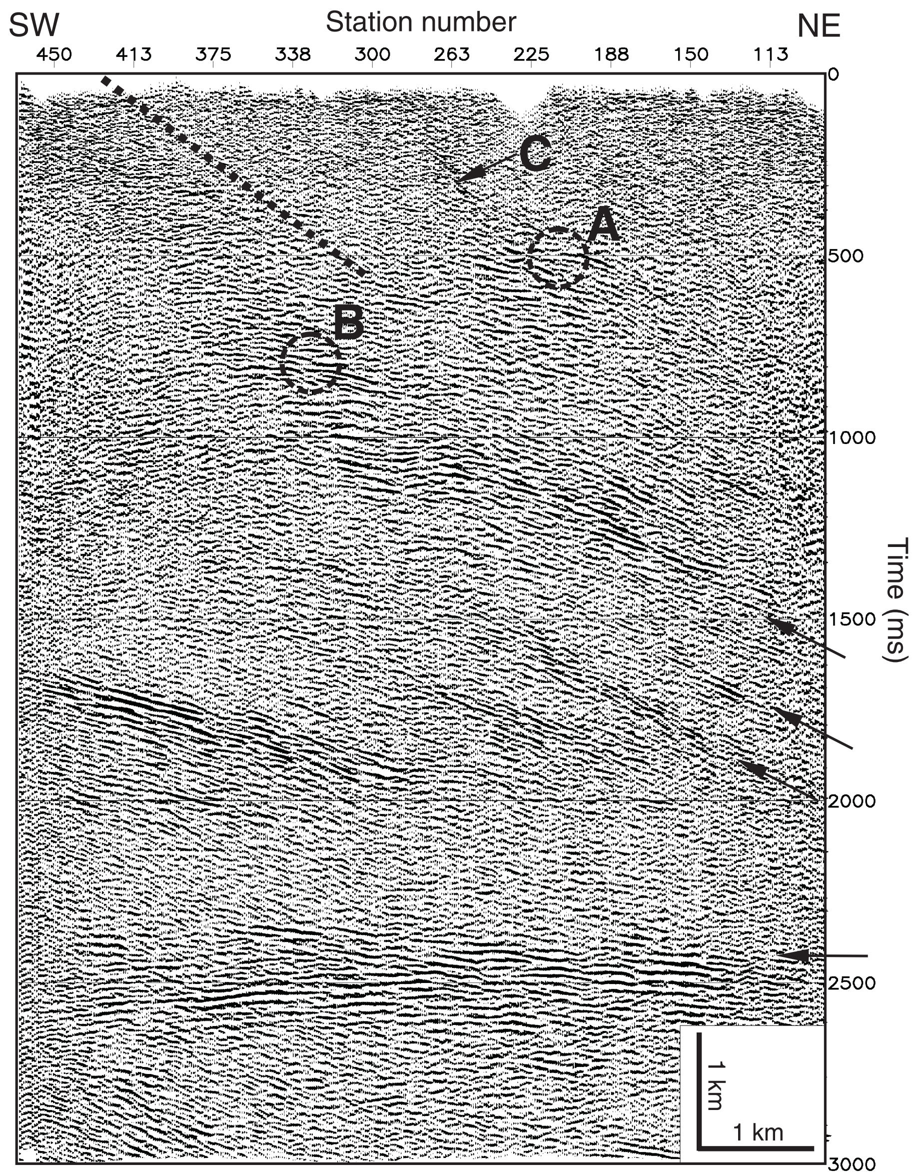

Figure 4.

*Sturgeon Lake line 1 dip moveout (DMO) stack (1:1 scale). **A** and **B** indicate diffractions, **C** points to steeply dipping, near-surface reflectivity, and the dotted line joins the apparent truncations of the horizontal reflectivity seen in the southwest part of the section. The arrows indicate reflections referred to in the text.*

meaningful interpretation was not available; however, useful observations can be made about the major features displayed on the seismic section.

Below 1 s on the DMO section (Fig. 4) we see a series of dipping interfaces (apparent dip of 20 to 30° NE) and a strong subhorizontal reflection package at 2.5 s. The dipping events are of varying strength, but continuous from station 463 to the northeast end of the section. The exception to this is the lowest layer of dipping reflections, which is strong at the southwest end of the line, but becomes incoherent at approximately the halfway point (around station 250). Above 1 s, the picture is more complex with strong, but patchy reflectivity in the southwest end of the line and a more transparent section to the northeast (at least above 0.4 s). At least two diffractions that can be identified; one with an apex at station 220 and 0.5 s (A on Fig. 4), and one at station 345 and 0.8 s (B on Fig. 4). The first diffraction (A) also appears to have a series of weaker diffractions below it, but they are not so continuous. Also of note in the top part of the section are some weak, steep, northeasterly dipping reflections (approximatley 40° dip) between stations 240 and 290 and 150–400 ms (C on Fig. 4). The subhorizontal reflections which make up the strong reflectivity in the west part of the line appear to truncate rather abruptly as they extend east. A hypothetical line (*see* dotted line on Fig. 4) joining these truncations (a fault?) would extend to surface at about station 420, near the contact between the older mafic volcanic group and the intrusive volcanic rocks to the south (Fig. 1).

The migrated section (Fig. 5) is noisier and contains more artifacts than the DMO section; however, it does clarify the picture somewhat in the upper section. Below 3 km the events are as described above except that the dipping events have moved updip to the southwest and appear to flatten towards the northeast end of the line. Above 3 km we see that

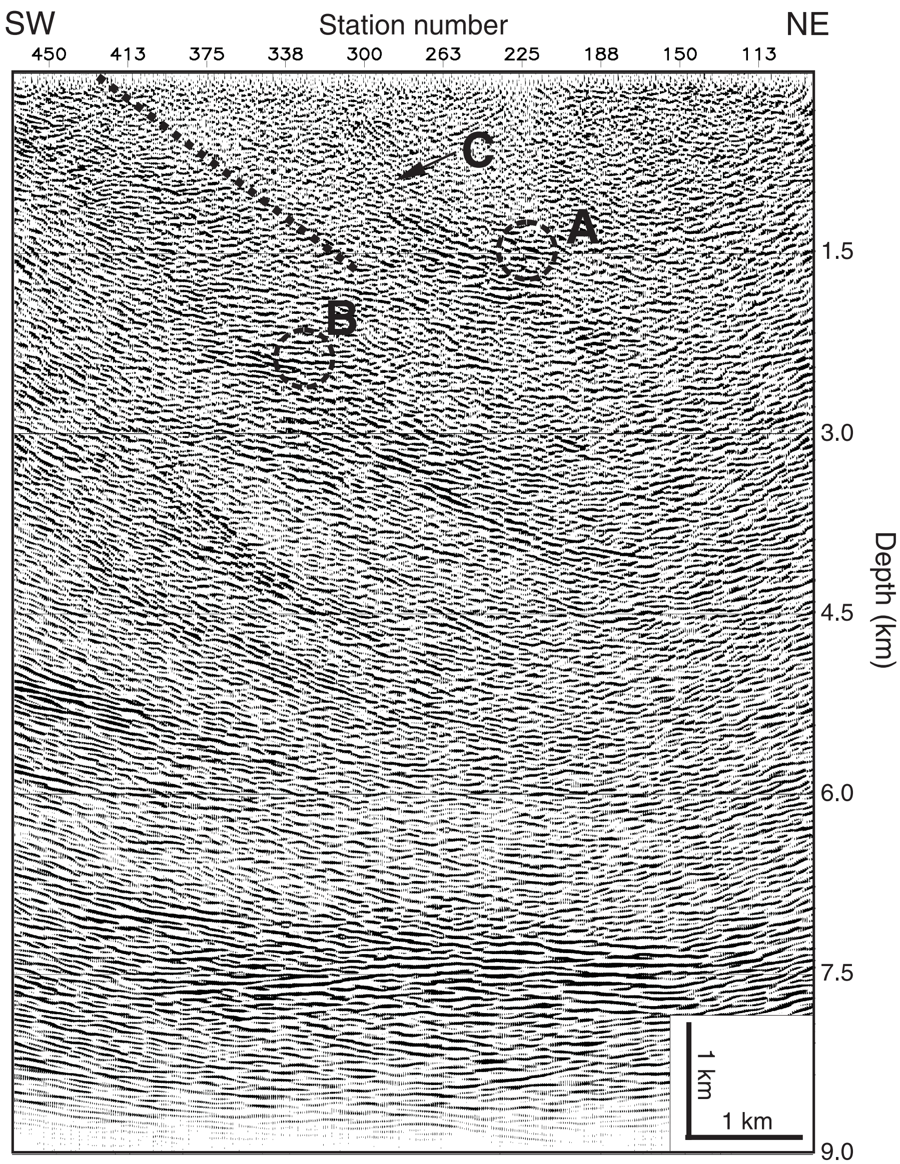

Figure 5.

Sturgeon Lake line 1 migrated stack (F-K migration at 6.0 km/s). See Figure 4 for description of features.

the two diffractions mentioned above have collapsed to fairly discrete zones of moderate- to high-amplitude reflections. The dipping reflections between stations 240 and 290 (referred to as C above) have steepened up, and now we can project them from the surface at approximately station 315 down to a package of subhorizontal reflections at 1.5–1.8 km (stations 210–220). Again, the subhorizontal events to the west end of the line appear to truncate against some east-dipping plane.

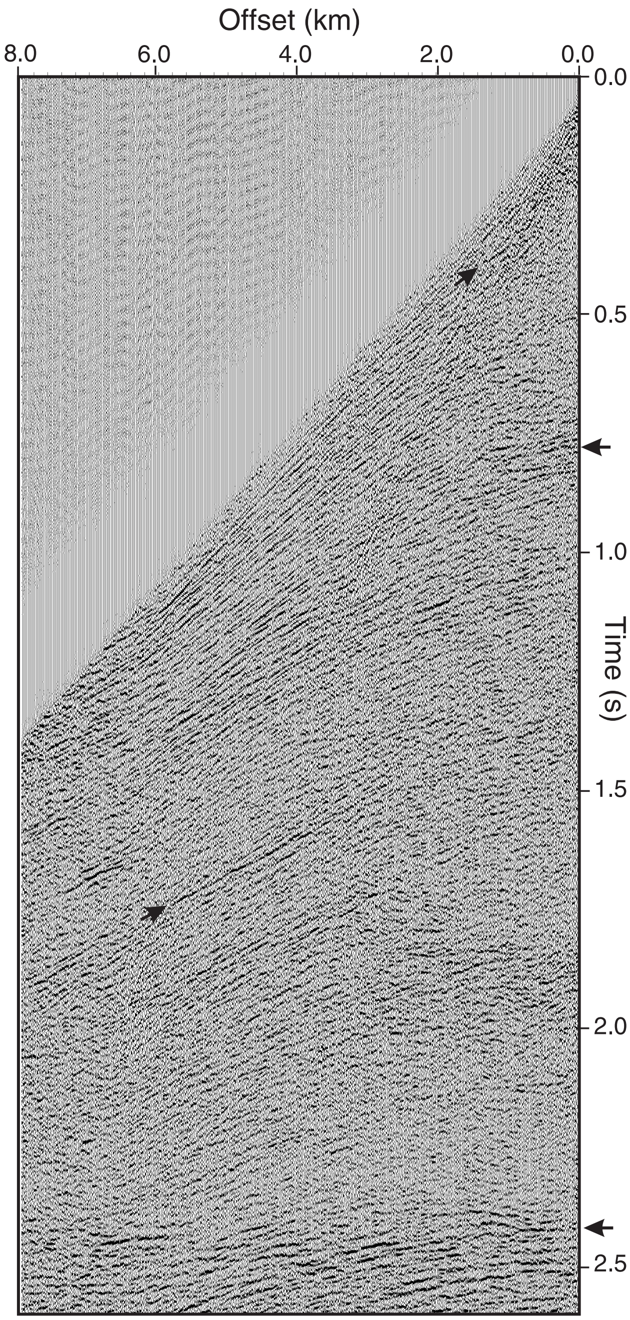

Figure 6. Common-scatter-point (CSP) gather at station 330. Offsets between 0 and 8 km are displayed. A 30–130 Hz spectral equalization with a 1.5 s window has been applied Arrows indicate reflections observed at various depths.

EQUIVALENT-OFFSET MIGRATION

Equivalent-offset prestack migration (EOM) has been applied to Sturgeon Lake line 1 using an ITA/Insight module developed at the GSC. Theory and various application of equivalent-offset migration are described by Bancroft et al. (1998). For a constant velocity, the typical NMO, DMO, CMP stack process is kinematically equivalent to prestack migration (Hale, 1984). However, EOM provides an efficient method for acquiring detailed velocity information, and comparisons with poststack migrations have shown that equivalent-offset migrations have better coherency and hence, are more interpretable (Bancroft, 1998). In the application of this method, common-scatter-point (CSP) gathers are assembled at the CDP locations along the processing line.

A CSP bin width of 20 m (twice the CDP spacing) was selected based on receiver spacing and trial-and-error testing with other data, generating 694 CSP gathers. Each CSP gather consisted of 500 traces with equivalent offsets between 0 and 10 000 m (Fig. 6). Note that different bin sizes were not tested. The migration velocity used to assemble the CSP gathers was 6.0 km/s and the maximum migration time was 3 s. The 3 s maximum migration time and the large offsets (10 km) were selected to avoid excessive smearing at depth.

The input traces for the CSP migration were preprocessed using the prestack processing flow described above, up to and including the DMO correction step. After the CSP gathers were assembled, NMO corrections and stacking were performed using ITA/Insight software. A single stacking-velocity function was used: 0.0 s, 5500 m/s; 0.2 s, 5900 m/s; 0.5 s, 6000 m/s. A NMO stretch mute factor of 50% was selected as a compromise between frequency content at shallow depth and imaging of shallow reflections. Stack sections using 0 and 30% stretch mutes were produced and showed strong subhorizontal events near the surface, which were probably caused by remnants of unmuted first-break energy.

The EOM prestack migrated section of the Sturgeon Lake line (Fig. 7) overall shows better continuity of events between 200 and 3000 ms than the F-K migrated section (Fig. 5). However, the migrated DMO section shows better images in the top 600 m and we attribute this difference to the wide aperture of the equivalent offset migration. Data points having an aperture close to 90° often include remnants of first-break energy, creating high amplitudes on the CSP gathers. These were attenuated by applying spectral equalization with a 500 ms sliding window. While this approach has greatly reduced the noise, some is still visible in the top 600 m and the data can no longer be considered ‘true amplitude’.

DISCUSSION AND CONCLUSION

We have observed strong reflectivity at Sturgeon Lake and some potentially interesting structures, both at depth and in the top 0.5 s. It is possible to compare this data to the LITHOPROBE regional seismic data that also crosses part of the Sturgeon Lake greenstone belt. The southern end of regional line 1A extends into the north end of the belt for

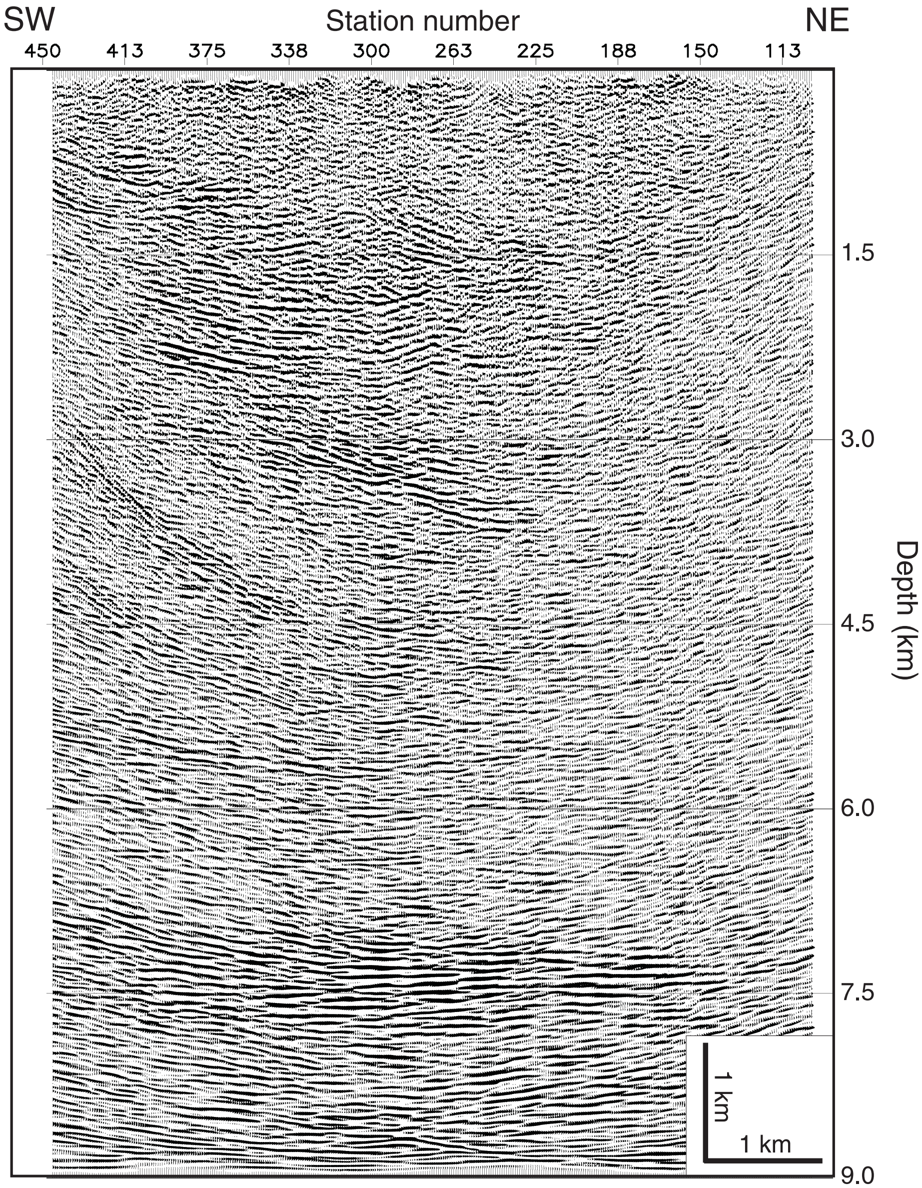

Figure 7.

Equivalent-offset migration stack of Sturgeon Lake line 1.

roughly 30 km ending approximately 40 km northeast of Sturgeon Lake line 1. The most prominent reflector in the upper crustal part of line 1A is a strong south dipping package that lies at 2.5–4.0 s (D. White et al., written communication, 1999). This event may correlate with the strong subhorizontal reflection we see at 2.5 s on the high-resolution line and indicate that this is a regional reflection underlying the greenstone belt.

The final stacks (DMO structure stack and migrated stack) could possibly be improved by more effort in at least two areas.

1. The refraction-statics solution appears to be at least adequate, but it may be that a better solution could be arrived at through the use of a more robust refraction-statics program. It is possible that this would lead to an improved image in the upper section.
2. The velocity analysis could be redone using the common-scatter-point gathers. The large equivalent offsets of the CSP gathers and better signal-to-noise ratio than standard common-midpoint (CMP) gathers translate into a more accurate velocity analysis. This would result in minor tuning of the velocities leading to a more accurate picture of the true velocities, and perhaps a slightly better image.

The key processing steps for these data were bandpass and 2-D spatial filtering (for coherent noise removal), refraction and residual statics (for improved signal continuity), and DMO (to enable the definition and application of the correct velocity function). In this case, the application of a prestack migration was worth the computational overhead and we would recommend the use of equivalent-offset prestack migration for all short- and moderate-length, high-resolution seismic lines in mining camps.

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