## GEOLOGICAL SURVEY OF CANADA
## OPEN FILE 7548

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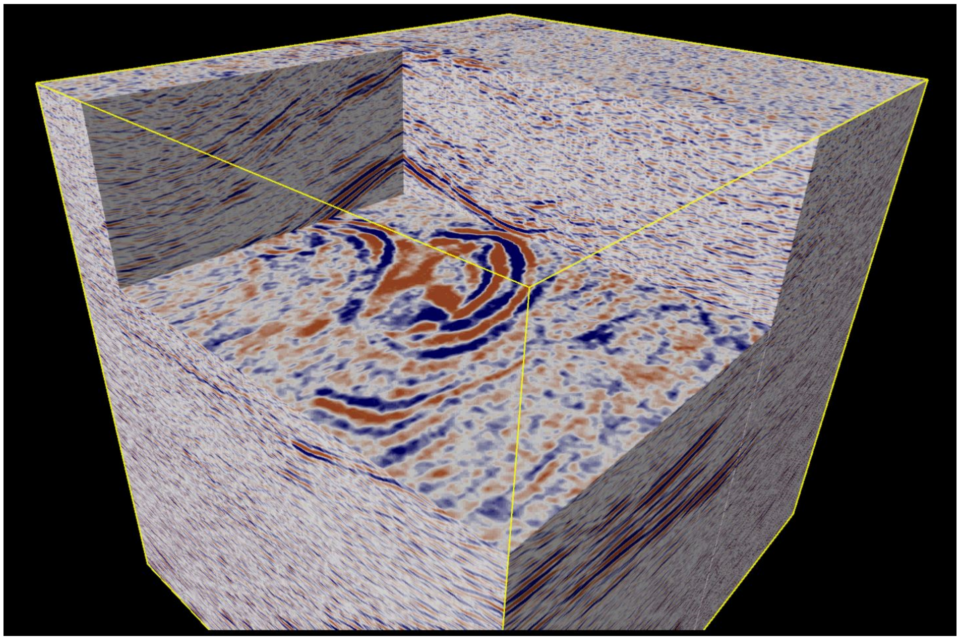

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## Introduction

Amongst the multitude of geophysical techniques that are used for mineral exploration, 3D seismic methods have the unique ability of providing deep (300-4000 m) penetration while maintaining high resolution (a few metres to tens of metres). However, their wide-spread use has been hampered by the relatively high cost of data acquisition, the dearth of documented case histories, and uncertainty in how to integrate results with traditional exploration geophysics. Advances in seismic recording technology over the last decade has increased by an order of magnitude (from 1000s to more than 10,000s) the number of simultaneous recording channels that are available for 3D imaging and has made available 3-component (3C) digital sensors. Three-component sensors measure ground motion in two horizontal and one vertical directions providing vector data that, in theory, should improve targeting of deep mineralized ore deposits. These technological advances have yet to be exploited for the purposes of deep mineral exploration.

As part of the methodology project of the TGI-4 program, the Geological Survey of Canada acquired a multicomponent 3D seismic data set over the Lalor Lake volcanogenic massive sulphide (VMS) deposit, located near Snow Lake Manitoba. The Lalor Lake VMS deposit was chosen as a test site as it provided an intact, well-characterized 27 Mt deep ore deposit with a rich catalog of geological and geophysical data, as well as extensive drill-core, and drillhole geophysical and geological logs. The 3C-3D seismic data were acquired to develop and test seismic imaging methods for deep exploration of VMS deposits. More particularly, the applicability and potential benefits of mode-converted Shear-waves (P-S) for deep exploration will be tested using the Lalor deposit as a test bed. Although this study is site- and commodity-specific, the results will be applicable to exploration elsewhere and will be adaptable for different deposit types.

In this Open File, we present the first release of the processed 3D data, a prestack-time migration volume of the P-waves observed on the vertical component of receivers. We also describe the acquisition parameters and the main parameters used for the processing of the data. The P-wave data constitute the first part of the larger study which is aimed at demonstration of the enhanced effectiveness of 3D seismic imaging that can be achieved by utilizing the full seismic wavefield available from 3-component surveys. In this larger study, we will complement traditional acoustic wave imaging with shear wave imaging obtained through converted-wave (P-S) processing. Results from the P-S processing sequence will follow latter in 2014.

## Geological Background

The Lalor Lake VMS deposit is located near Snow Lake, Manitoba, about 200 km east of Flin Flon, and lies within the Snow Lake arc assemblage in the eastern part of the Paleoproterozoic Flin Flon Greenstone Belt (Figure 1). The Snow Lake assemblage (Figure 2) is a 20 km wide and 6 km thick section and comprises three successions (Bailes and Galley, 1999) that display geodynamic evolution from a `primitive arc' (Anderson sequence to the South) to a `mature arc' (Chisel sequence) to an `arc-rift' (Snow Creek sequence to the Northeast) setting. The Chisel sequence comprises a variety of intercalated lithologies including mafic volcanic flows, volcaniclastic rocks, several rhyolite flow complexes, and numerous synvolcanic intrusions (Galley et al., 2007). The lower part of the Chisel sequence hosts many Zn-Pb-Cu-Ag-Au-rich deposits (Chisel, Chisel North, Ghost, Lost, Photo and Lalor Lake) in the Snow Lake area. The VMS deposits are associated with extensive hydrothermal alteration of the footwall rocks. Semi-conformable zones of alteration mapped regionally and small discordant alteration pipes located below the VMS deposits do not occur in basalt flows and volcaniclastic rocks of the upper Chisel sequence (Galley et al., 1990).The three successions of the Snow Lake assemblage are dominated by fold-thrust style tectonics and are metamorphosed at lower to middle almandine-amphibolite facies (Bailes and Galley, 1999). The Lalor Lake area also comprises felsic and mafic intrusive rocks which occur as extensive units.

The Lalor deposit was discovered in 2007 by Hudson Bay Mining and Smelting (HBMS). The deposit is a 27 Mt deposit located at ~800 m depth with metal contents of 9% Zn, 0.6% Cu, 1.4 g/t gold and 25.5 g/t silver. The Lalor Lake deposit is located at the contact between the lower and upper Chisel sequence and is associated with an extensive hydrothermal alteration system. The mineralization trends to the W-WNW and dips between $10^{o}$ and $30^{o}$ to the NNE. The deposit extends approximately over 900 m in the north-south direction and 700 m in the east-west direction. The Lalor Lake VMS deposit comprises several mineralized zones starting at approximately 570 m depth and extending to a depth of approximately 1170 m. The ore zones are stacked and embedded in moderately–dipping but highly deformed and altered stratigraphy. Ore zones 10 and 11 are the shallowest and generally comprise near-solid to solid sulphide mineralization with fine to coarse grained pyrite crystals (1-5 mm) and sphalerite occurrences interstitial to the pyrite. The sulphide lenses in the footwall to zones 10 and 11 tend to be disseminated or stringer sulphides. Gold and silver enriched zones occur near the margins of the sulphide lenses and in the local silicified footwall alteration (Galley et al., 2007). These silicified areas often correlate with disseminated to stringer chalcopyrite and galena. The top of the Lalor Lake VMS deposit is near a decollement contact with the overturned hanging wall rocks of the upper Chisel sequence. The hanging wall display a diversity of rock types including mafic, felsic volcanic rocks, mafic to volcanoclastic units, mafic wacke, crystal tuff, and fragmental unit (Galley et al., 2007).

Footwall alteration generally includes extensive zones comprising dominant sericite-quartz-pyrite and more localized chlorite-quartz-pyrite. However, at least 11 alteration styles were observed including sericite-pyrite-biotite-kyanite, anthophyllite-garnet-biotite-staurolite, carbonate-chlorite-amphiboles alteration styles (Caté et al., 2013). Zones of silicification, Fe-Mg metasomatism, and large garnet-amphibole underlie the Chisel, Lost, Ghost, and Lalor VMS deposits within the Chisel sequence (Skirrow and Franklin, 1994; Bailes and Galley, 1999; Caté et al., 2013). Large crystals of kyanite, staurolite, garnet, cordierite, anthophyllite, plagioclase, biotite, and muscovite are prominent in the footwall and are indicative of metamorphosed hydrothermal alteration associated with VMS deposits (Galley et al, 2007). Alteration also includes zones of finely disseminated sulphides (pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena).

## Data acquisition

The survey parameters were chosen not to produce the best images of the ore zones but rather to test exploration-like parameters using the Lalor deposit as a test bed. The survey parameters should produce a detectable signature from ore zones located a great depth. A much tighter grid of source and receiver lines would have been required for ore delineation (see Malehmir et al., 2012 for an example of seismic mine-scale delineation). The 3D survey geometry (Figure 3) covers an area of approximately 16 km$^2$ with the Lalor VMS deposit located approximately in the centre of the grid. The survey comprises 15 shot lines with a NW-SE orientation, and 16 receiver lines oriented SW-NE (Figure 3). Shot lines were spaced every 365 m with a source interval of 50 m, whereas receiver lines and receiver spacing are 250 m and 25 m, respectively.

The Lalor 3C-3D seismic survey was acquired during the winter of 2013 by SAExploration under contract with Natural Resources Canada. The acquisition was split into three parts that included line cutting, drilling and loading of explosives in shot holes, and data recording. Surveying of the shot and receiver positions was done simultaneously with the line cutting and drilling of the shot holes.

Lines were cut using mulchers guided with GPS systems. Where necessary, mulchers deviated from the planed shot and receiver lines to avoid major terrain obstacles such as large boulders, steep areas, and cliffs, and to minimize the amount of cut merchantable timber. Receiver lines had a width of 1.75 m whereas source lines were 2.25 m wide to provide access of low-impact seismic (LIS) drills. A total of eight LIS drills were used to prepare shots for the survey. Shot holes were 5m deep and loaded with 0.5 kg of explosives. Shot holes were tamped with bentonite and cuttings from the drilling. The 908 shot points were completed in approximately 8 days.

A total of 2685 3-C digital accelerometers (Sercel DSU3) were used during the data acquisition. The DSU3 rely on the Micro-machined Electro-Mechanical Sensor (MEMS) technology to provide a broadband linear response from DC to 800 Hz, and very low distortion. The generally cold temperatures during the 3D acquisition resulted in solidly frozen near-surface conditions which allowed excellent ground-to-geophone coupling. All receivers were live (one patch) during data recording. Data acquisition was completed with no incidents and in compliance with environmental regulation. Table 1 shows the main acquisition parameters used for the 3D seismic data acquisition.

The quality of the raw shot gathers ranges from poor to excellent with most shot gathers generally having good signal-to-noise ratio. The raw shot gathers with good quality seismic data have clear first arrivals at largest offsets (up to 4 km). Most of the poor-quality shot gathers are located in areas with muskeg which strongly attenuates seismic waves. Despite the presence of high-amplitude source-generated noise (e.g., shear-wave, ground-roll, and occasional air-blast) and occasional ambient noise (e.g., mining activities and wind), clear reflections can be identified from many raw shot gathers. Figure 4 shows a typical raw shot gather recorded on receiver lines 133 to 141. Analysis of amplitude spectra (Figure 5) for most shot gathers indicates that frequencies as high as 300 Hz were recorded, but in general, the dominant frequencies are in the range of 40−250 Hz. Much of the low frequency noise on shot gathers is associated with ground-roll and refracted shear-wave energy and are typically below 35 Hz.

## Data Processing

The processing of the 3D-3C data comprises two parts; one for the conventional processing of P-wave data recorded on the vertical component, and the other for the processing of P-S mode-converted waves recorded on the horizontal components. Only the conventional P-wave processing is presented in this Open File. Data processing was conducted by Sensor Geophysical Limited. Amongst the processing approaches tested by Sensor Geophysical, the prestack-time migration (PSTM) sequence provided the most detail in the shallow part of the sections and remarkably coherent reflections in the deeper part of the seismic volume. Details about the processing sequence can be found in Table 2. The critical processing steps included refraction statics, coherent noise attenuation, and Common Offset

Vector (COV) binning and data regularization prior to prestack-time migration. First breaks were automatically picked. Picked times on the five receiver lines nearest to every shot point were reviewed and manually edited. Final first breaks were input to GLI3D to obtain a refraction statics solution for a single layer with a weathering velocity of 610 m/s and a replacement velocity of 5900 m/s. First break picks for offsets between 62.5 m and 3000 m were used in the calculation. Both f-k filtering and eigenimage filtering were applied to common source gathers to attenuate the strong amplitude, low frequency coherent noise observed on all records. The f-k filter effectively attenuated the refracted noise present on the receiver lines close to the source location. However, f-k filters were less effective on receiver lines further away from the source. An eigenimage filter was applied to common source gathers to attenuate this residual noise. The filter was applied to all but the three receiver lines nearest each source. The filter focussed on noise localized in a narrow time window and frequencies between 4-32 Hz.

The presence of crooked and irregularly spaced source and receiver lines, combined with missing or skidded shots can compromise the prestack migration of 3D land seismic data (Cary and Li, 2005). To minimize the effects of irregular acquisition geometry, the seismic data were binned into common offset vector (COV) gathers which were subsequently independently migrated. A total of 154 natural and overlapping COV bins were defined for the Lalor survey. COV bins have a width of 500 m in the crossline offset direction and 730 m in the inline offset direction. Source-receiver reciprocity was invoked to populate the COVs and further helped to compensate for irregular source geometries. COV data were regularized using immediate common depth point (CDP) neighborhood interpolation and filtered (F-XY) prior to migration. Figure 6 presents a perspective view of the PSTM to show to overall quality of the data. The PSTM data is characterized by numerous reflections including in the shallow part of the seismic volume. Continuous reflections on a time slice at 730 ms (about 2.1 km depth) define a bowl-shape structure near the base of the Chisel sequence. Interpretation of the data will follow in another publication. A digital version of the processed 3D data (SEGY format) is provided in this Open File. Table 3 provides the trace header byte positions for the digital SEGY file.

## Summary

As part of the methodology project of the TGI-4 program, the Geological Survey of Canada acquired a 3D-3C seismic data set over the Lalor Lake VMS deposit, located near Snow Lake Manitoba. The Lalor Lake VMS deposit was chosen as a test site as it provided an intact, well-characterized 27 Mt deep ore deposit with a rich catalog of geological and geophysical data. The 3D-

3C seismic data was acquired to develop and test seismic imaging methods for the deep exploration of VMS deposit. We described the field acquisition parameters and the main parameters used for the processing of the data. The processing focussed on P-wave data recorded on the vertical receiver component. The P-wave data reveals many reflections at shallow depth and remarkably continuous reflections close to the base of the Chisel sequence. The P-wave data set presented in this Open File is one part of a larger study aiming at demonstrating the enhanced effectiveness of 3D seismic imaging by utilizing the full seismic wavefield available from 3-component surveys. A digital version of the prestack-time migration of the data (P-P) is also a component of this Open File.

## Acknowledgments

The 3C-3D data was acquired by SAExploration and processed by Sensor Geophysical Limited. We thank J. Mackie (SAExploration) and R. Couzens (Sensor Geophysical). The acquisition of this 3D-3C seismic data would not have been possible without the collaboration of HBMS. We thank P. Dueck, G. Taylor, B. Janser at the Flin Flon exploration office, T. Butt, T. Scheres at the Lalor mine site, and all HBMS employees that made this project feasible.

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## Table 1. Acquisition parameters for the 3D-3C Lalor seismic survey.

| | |
|---|---|
| Instrument/accelerometer | Sercel 428/DSU3 (3C) |
| Traces/record | 3 x 2685 |
| Aux/ record | 2 |
| Sample interval | 1 ms |
| Sample /trace | 4001 |
| Filters alias | 400 Hz |
| Source type/ Source depth | explosive (0.5 kg)/ 5m |
| No. of shots | 908 |
| Source spacing/line spacing | 50 m/ 365 m |
| Receiver spacing/line spacing | 25 m/ 250 m |
| No. of source/receiver lines | 15/16 |
| Patch | All live |
| Survey area | 16 $km^2$ |

## Table 2. Processing parameters for the prestack time-migration flow

| Step | Parameters |
|---|---|
| **1.** | Reformat, record length 4.0 seconds, sample rate 1 ms |
| **2.** | Geometry Assignment, 3D Binning, CDP Bin size 12.5 m x 25.0 m; |
| **3.** | Trace kills |
| **4.** | Refraction Static Corrections, Datum = 400 m, Vr = 5900 m/s, 1 Layer |
| **5.** | Surface Consistent Amplitude Corrections; Spherical divergence correction |
| **6.** | Instrument Compensation |
| **7.** | Shot f-k Filter to Attenuate PSP Refracted Arrivals |
| **8.** | Eigen-image Filtering to Attenuate PSP Refracted Arrivals; 2 dB/sec gain |
| **9.** | Surface-Consistent Deconvolution<br>Resolved: Source, Receiver, Offset Applied: Source, Receiver<br>Operator Type Spiking, Operator length 100 ms, Prewhitening 0.01%<br>Design window 400-2350 ms at 0 m, 950-2450 ms at 5000 m offset<br>Offsets used in design 500-4000 m |
| **10.** | TV Spectral Whitening, 250 ms window, 4/10-120/140 Hz, 10 operators |
| **11.** | Surface-Consistent Statics, Max shift 12 ms, window 500-3500 ms |
| **12.** | CDP Trim Statics, f-xy Filtered Model, Max shift 4 ms, window 400-3400 ms |
| **13.** | Normal Moveout Correction |
| **14.** | Front-End Mute, 0, 150, 900 ms at 750, 1075, 5000 m offsets |
| **15.** | Automatic Gain Control, 750 ms window length, 15/25-80/100 Hz design band |
| **16.** | 3D COV Binning: 730 m x 500 m bins, 154 Overlapping COV bins |
| **17.** | COV Regularization; COV F-XY Filtering, 3x3 point operator, 100 ms window |
| **18.** | AGC; NMO Restoration |
| **19.** | Prestack Kirchhoff Time Migration |
| **20.** | Front-End Mute, 0, 150, 1250 ms at 750, 1000, 5000 m offsets |
| **21.** | CDP Simple Mean Stack, 0 ms bulk shift |
| **22.** | Ormsby Filter, 10/15-100/120 Hz; Trace Equalization, Mean window 200-2500 ms |

## Table 3. SEGY Trace Header Byte Positions for Migrated CDP Gathers.

| Header | Format | Starting byte |
|---|---|---|
| Trace Sequence Number | 4I | 1 |
| Inline Number | 4I | 9 |
| Crossline Number | 4I | 13 |
| CDP Name | 4I | 17 |
| CDP Number | 4I | 21 |
| Trace Type | 2I | 29 |
| CDP Elevation | 4I | 41 |
| Datum Elevation | 4I | 53 (400 m) |
| Replacement Velocity | 4I | 57 (5900 m/s) |
| Stack fold | 4I | 65 |
| CDP X-Coordinate | 4I | 73 |
| CDP Y-Coordinate | 4I | 77 |
| Time to floating datum | 2I | 97 |

UTM ZONE 14N COORDINATES NAD83
Grid Bin Center (Inline 1, Crossline 1) = (427071.7, 6084548.0)
Grid Bin Center (Inline 1, Crossline 360) = (423746.9, 6081534.0)
Grid Bin Center (Inline 152, Crossline 1) = (429606.9, 6081751.0)
Grid Bin Center (Inline 152, Crossline 360) = (426282.2, 6078737.0)
Sample Interval = 1000 microseconds. Samples Per Trace = 4001.
Trace Length = 4000.00 ms. Data Format = IBM 32 bit floating point.
Number of Traces = 54720.

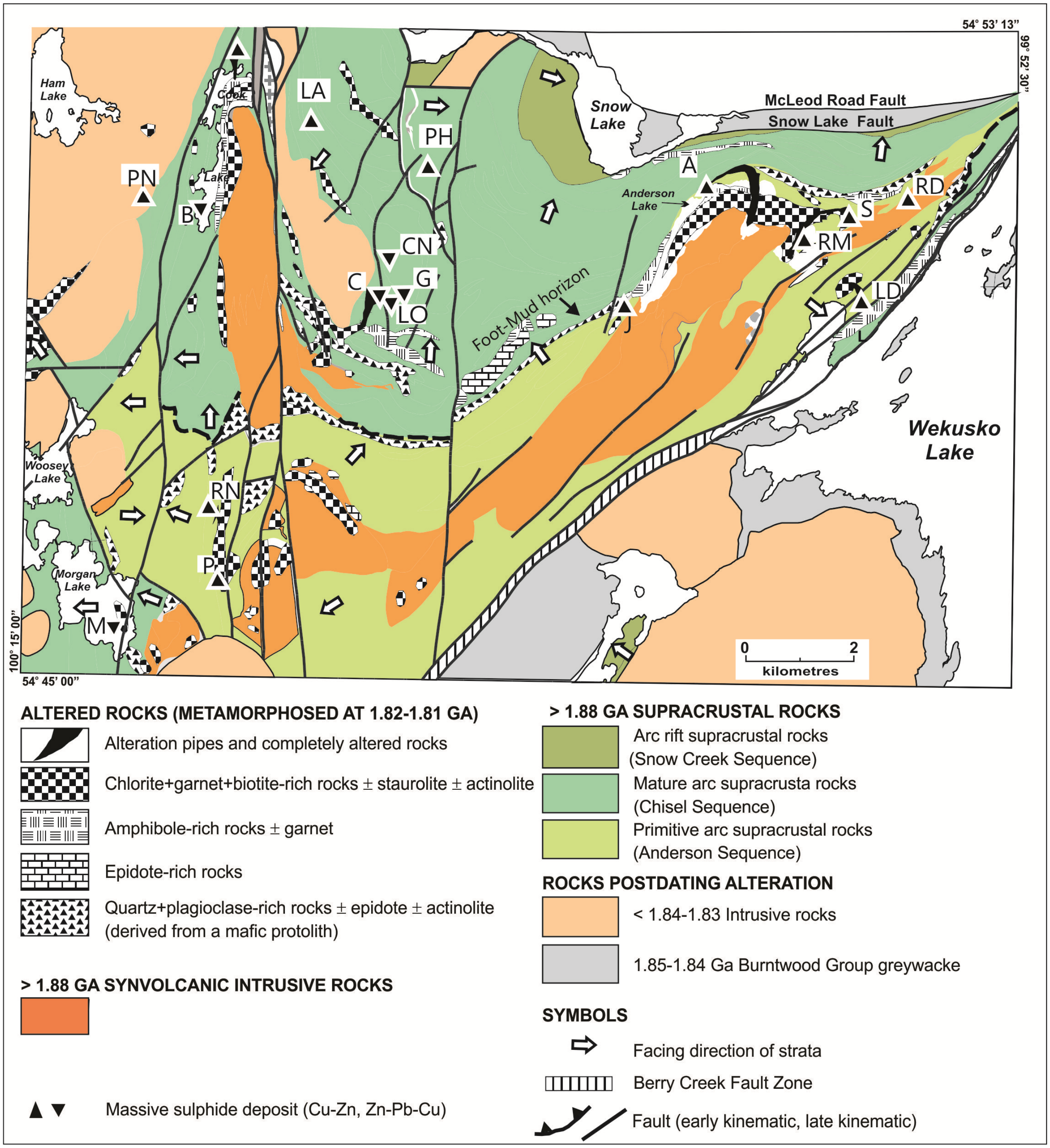

Figure 1. Generalized geology map of the Snow Lake arc assemblage, including large-scale metamorphosed hydrothermal alteration zones, and VMS deposits and major occurrences. A=Anderson; B=Bomber zone; C=Chisel Lake; CN=Chisel North; G=Ghost; J=Joannie zone; LA=Lalor; LO=Lost; LD=Linda zone; M=Morgan Lake zone; P=Pot Lake zone; PH=Photo Lake; PN=Pen zone; RD=Rod; RM=Ram Zone; RN=Raindrop zone; S=Stall Lake. Modified from Bailes and Galley (1999).

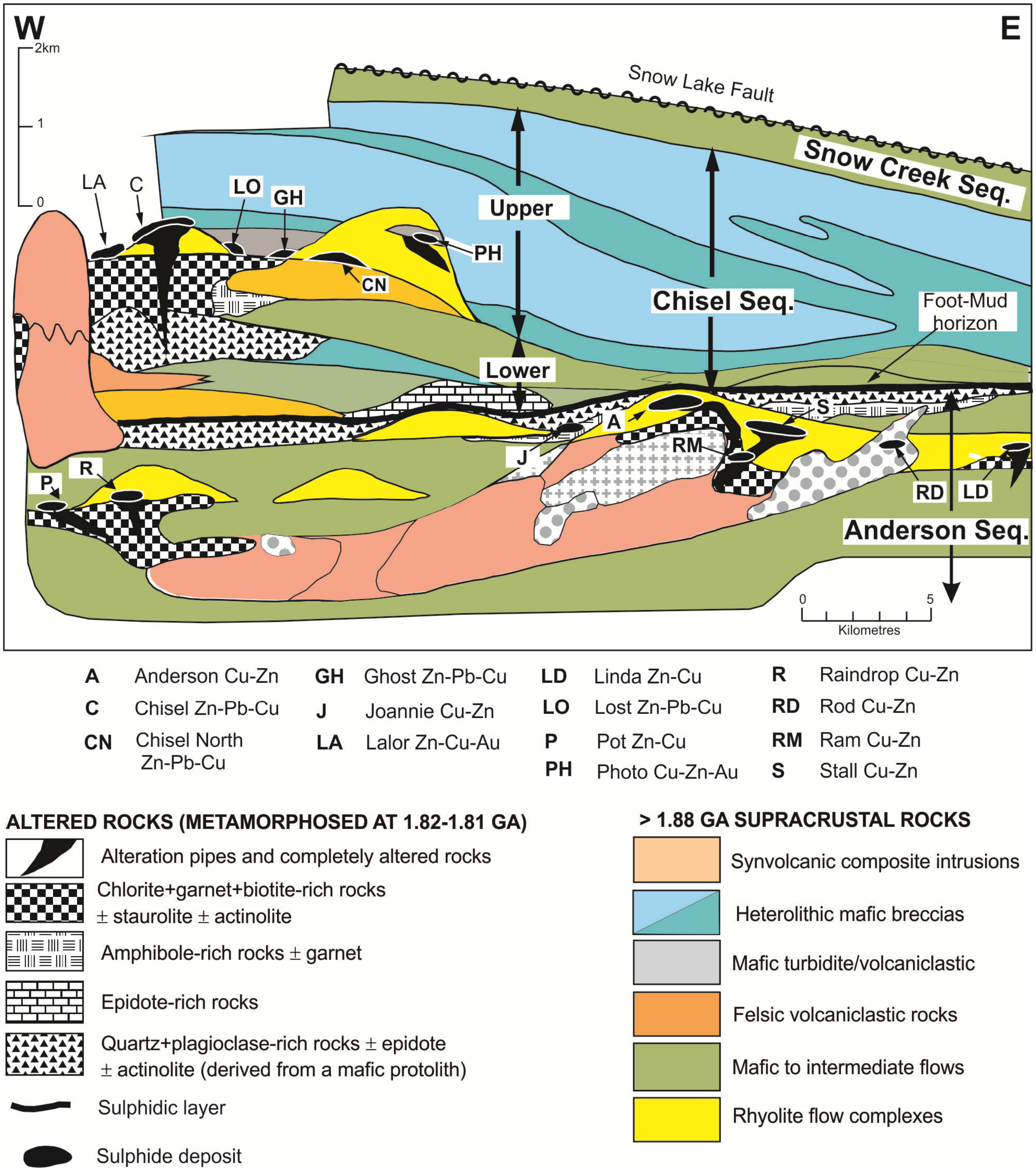

Figure 2. Schematic stratigraphic section through the Snow Lake arc assemblage showing the distribution of hydrothermal alteration zones, and their relationship to known ore deposits in that area (modified from Bailes and Galley, 1999). The Lalor Lake deposit (LA) is located at the contact between the upper and lower Chisel sequence.

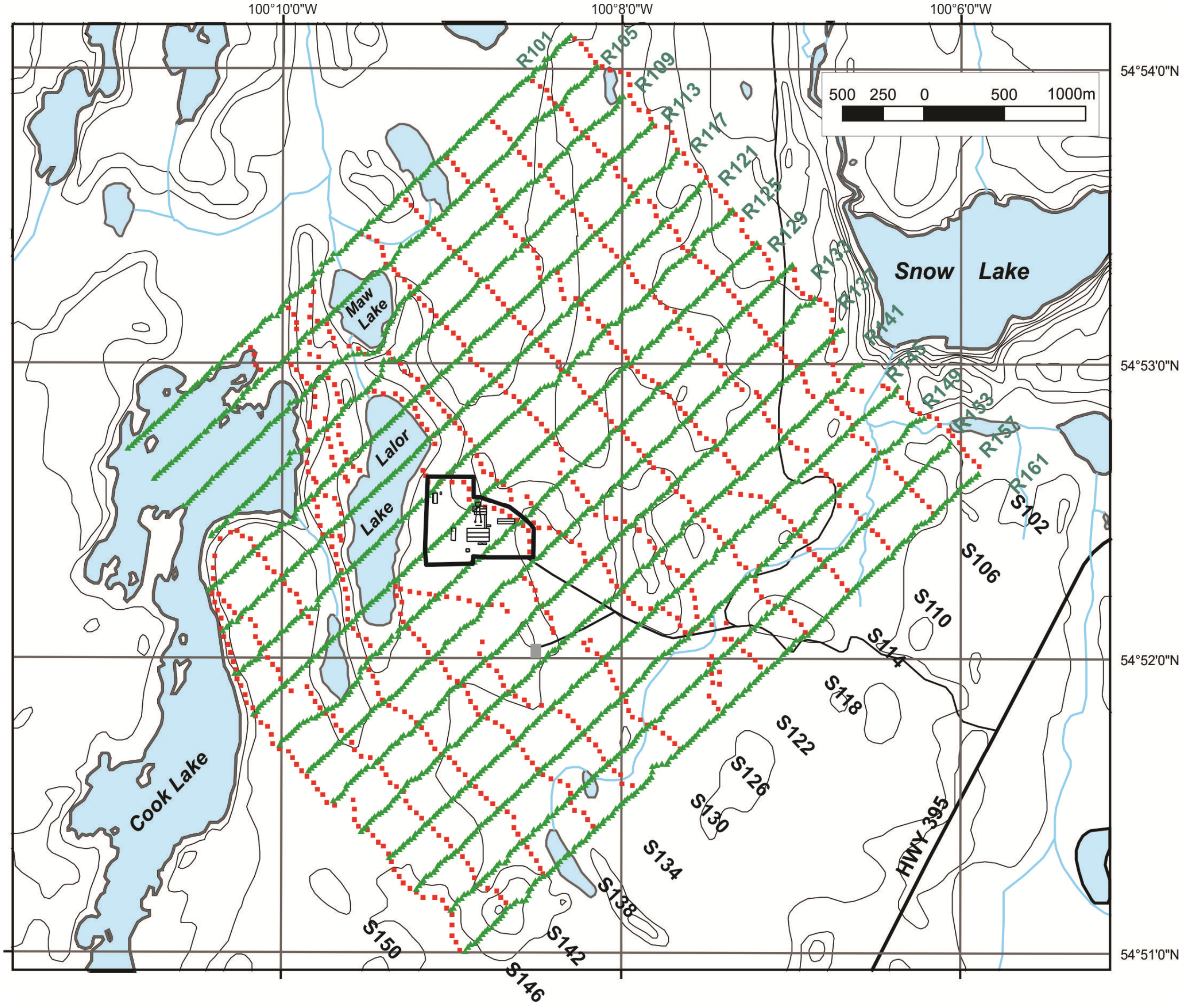

Figure 3. Acquisition geometry of the 3D-3C Lalor seismic survey. Receiver locations are shown in green whereas shot points are shown in red. The mine site area and main road are shown in black (black polygon for the mine site). The survey comprises 908 shot points and 2685 multi-component receivers.

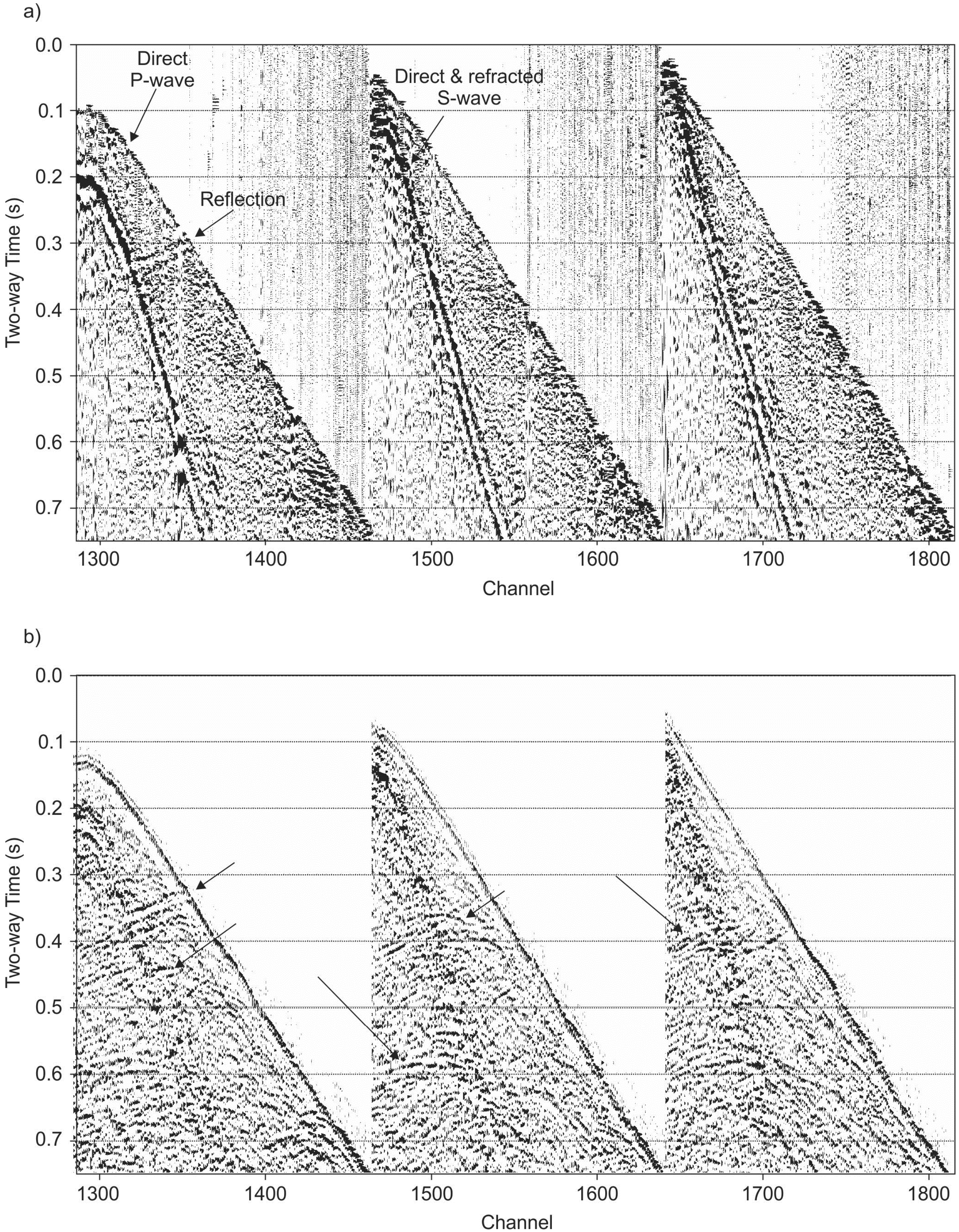

Figure 4. (a) Example of a raw shot gather on three receiver lines. (b) Same shot gather after some processing (refraction static corrections, coherent noise attenuation and surface-consistent deconvolution). Arrows point to a few reflections.

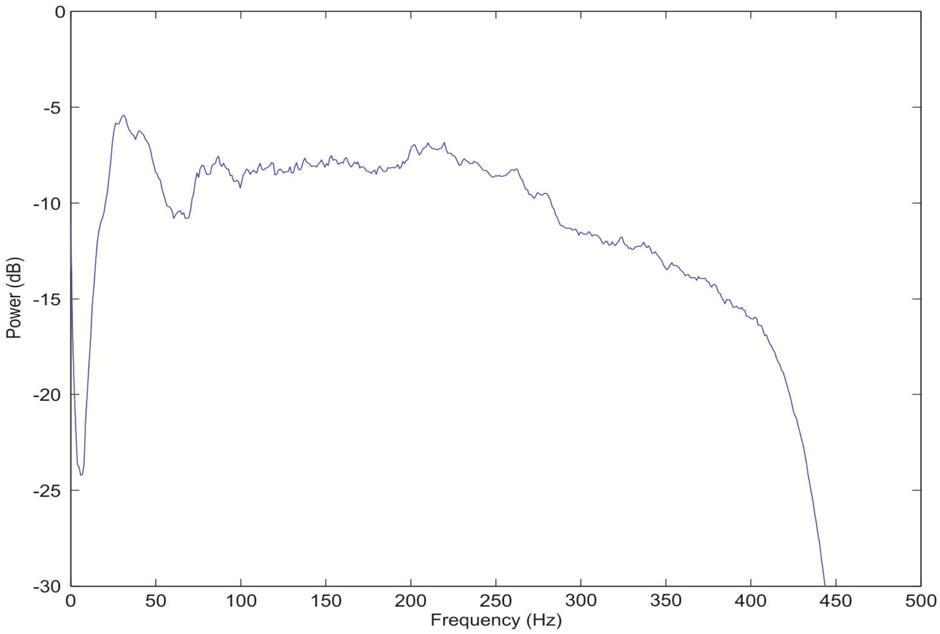

Figure 5. Power spectrum of a raw shot gather from the Lalor 3D-3C data (vertical component). Signal up to 300 Hz were recorded on this shot gather.

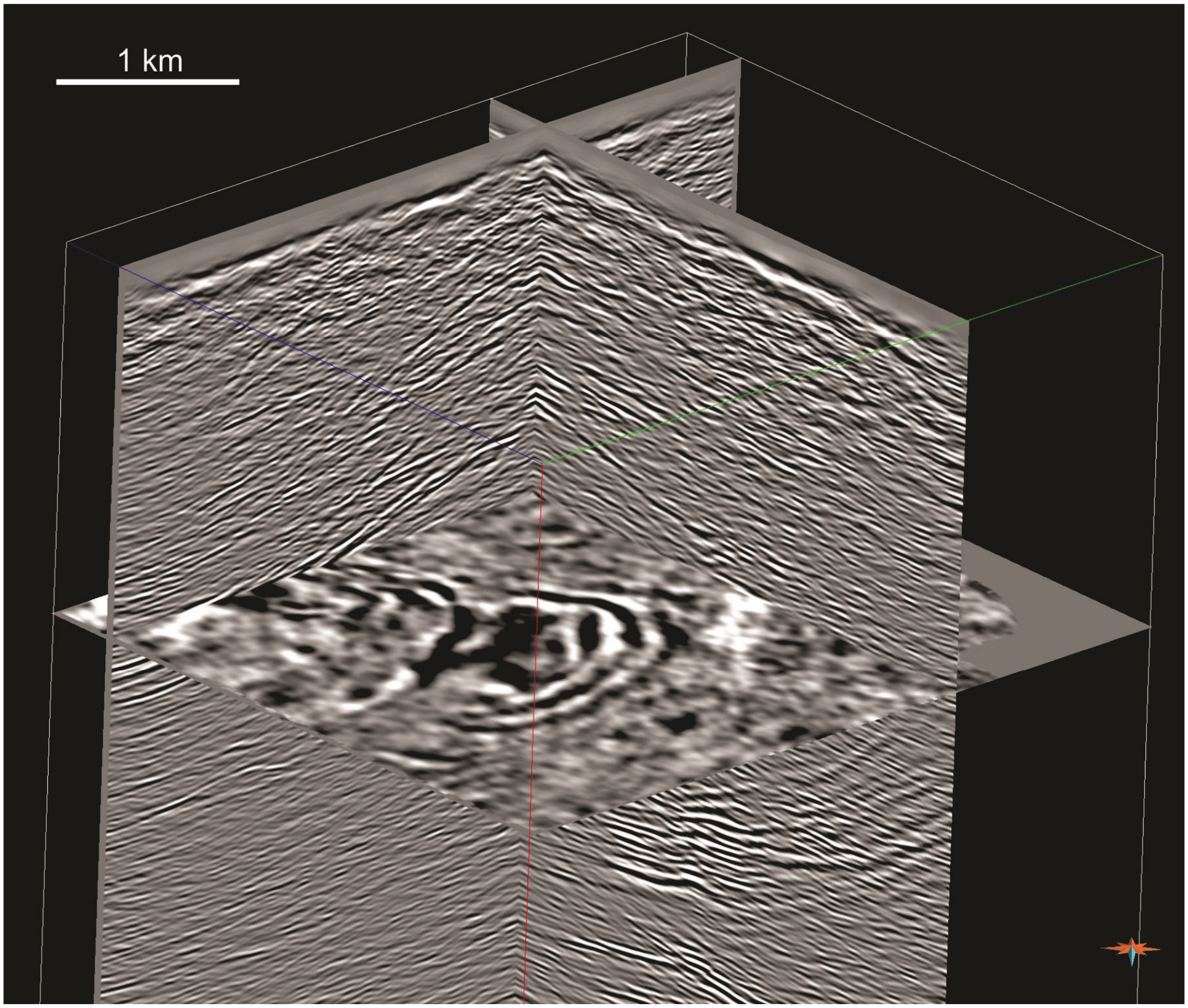

Figure 6. Perspective view (looking south) of the prestack-time migrated seismic volume. The time slice at 730 ms (approximately 2.1 km depth) shows remarkably continuous reflections defining a bowl-shape structure. Numerous reflections are also observed at shallow depth.