



SEISMIC EXPLORATION FOR VMS DEPOSITS, MATAGAMI, QUÉBEC

Adam, E.^[1], Arnold, G.^[2], Beaudry, C.^[2], Matthews, L.^[3],
Milkereit, B.^[4], Perron, G.^[5], and Pineault, R.^[6]

1. Geological Survey of Canada, Ottawa, Ontario, Canada
2. Noranda Mining and Exploration Inc., Rouyn-Noranda, Québec, Canada
3. Noranda Mining and Exploration Inc., Calgary, Alberta, Canada
4. Kiel University, Germany
5. Geological Survey of Canada, Ottawa, Ontario, Canada
6. Val d'Or-Sagax, Lima, Peru

ABSTRACT

The south flank of the Galinée anticline in the Matagami mining camp is a favourable geological setting for reflection seismic profiling; the stratigraphy is moderately dipping and large acoustic impedances exist between rock units. Integrated high-frequency seismic profiling and borehole geophysical logging began in 1990 to evaluate their usefulness for deep (>500 m) mineral exploration. These surveys show that seismic methods are capable of mapping the volcanic stratigraphy that hosts the deposits in the Matagami camp and that strong reflections occur at the interfaces between gabbro and rhyolite units. Additional physical rock property measurements and a vertical seismic profile were acquired to study the reflectivity of the Bell Allard deposit, a 6 million tonne massive sulphide body discovered in 1992 at a depth of 1 km. Seismic forward modelling of this deposit predicted a spatially complex diffraction response that could be best resolved using 3-D seismic reflection methods. Therefore, a 20 km² 3-D seismic experiment was designed and completed in 1996 to image the Bell Allard deposit. The results show that the ore body possesses a distinctive seismic response. Thus, 3-D seismic methods are suitable for mapping deep volcanic stratigraphy and can, under certain conditions, provide direct detection of massive sulphide bodies.

INTRODUCTION

Exploration for new massive sulphide deposits in mature mining camps within the Abitibi greenstone belt and elsewhere rely heavily on deep drilling to test prospective stratigraphic contacts since conventional geophysical methods are generally limited to the first few hundred metres depth. As the search for new reserves expands to greater depths, exploration costs increase geometrically providing a strong impetus to develop alternate methods of prospecting favourable horizons. The seismic technology research project at Noranda Mining and Exploration Inc. began in 1990 in response to this need and, in part, because of the opportunity provided by the LITHOPROBE multidisciplinary study of the Abitibi subprovince of the Canadian Superior Province.

Following the completion of two high-resolution seismic profiles on the south flank of the Matagami volcanic complex in 1990 and 1993 along with a number of complementary studies to define physical rock properties (*in situ* and laboratory measurements) (Cinq-Mars *et al.*, 1995; Salisbury *et al.*, 1996), theoretical 3-D seismic responses (Adam *et al.*, 1996) and optimal seismic acquisition parameters, a decision was made to carry out a 20-km² 3-D seismic reflection survey over the south flank in an area overlying the newly discovered Bell Allard deposit. The

primary survey objectives were to resolve the seismic characteristics of the deposit in relation to the host rocks, to define other similar signatures within the survey area, and to provide operational parameters for costing future surveys.

This communication presents preliminary results of the 3-D seismic survey in Matagami and implications for VMS exploration in this camp and in similar geological settings.

GEOLOGICAL SETTING

The Matagami volcanic complex is located in the eastern part of the Haricana-Turgeon belt of northern Abitibi (Lacroix *et al.*, 1990) and was formed by two major phases of predominantly tholeiitic volcanism. The early phase produced dacites and rhyolites of the Watson Lake Group (Figure 1), whereas the younger phase, which produced the Wabasse Group, was dominated by basaltic volcanism with subordinate felsic activity, and was accompanied by mafic-dominated sub-concordant intrusions (Piché *et al.*, 1993; Beaudry and Gaucher, 1986). A cherty, sulphidic chemical sediment known as the Key Tuffite marks the contact and hiatus between the two formations and is traceable for many

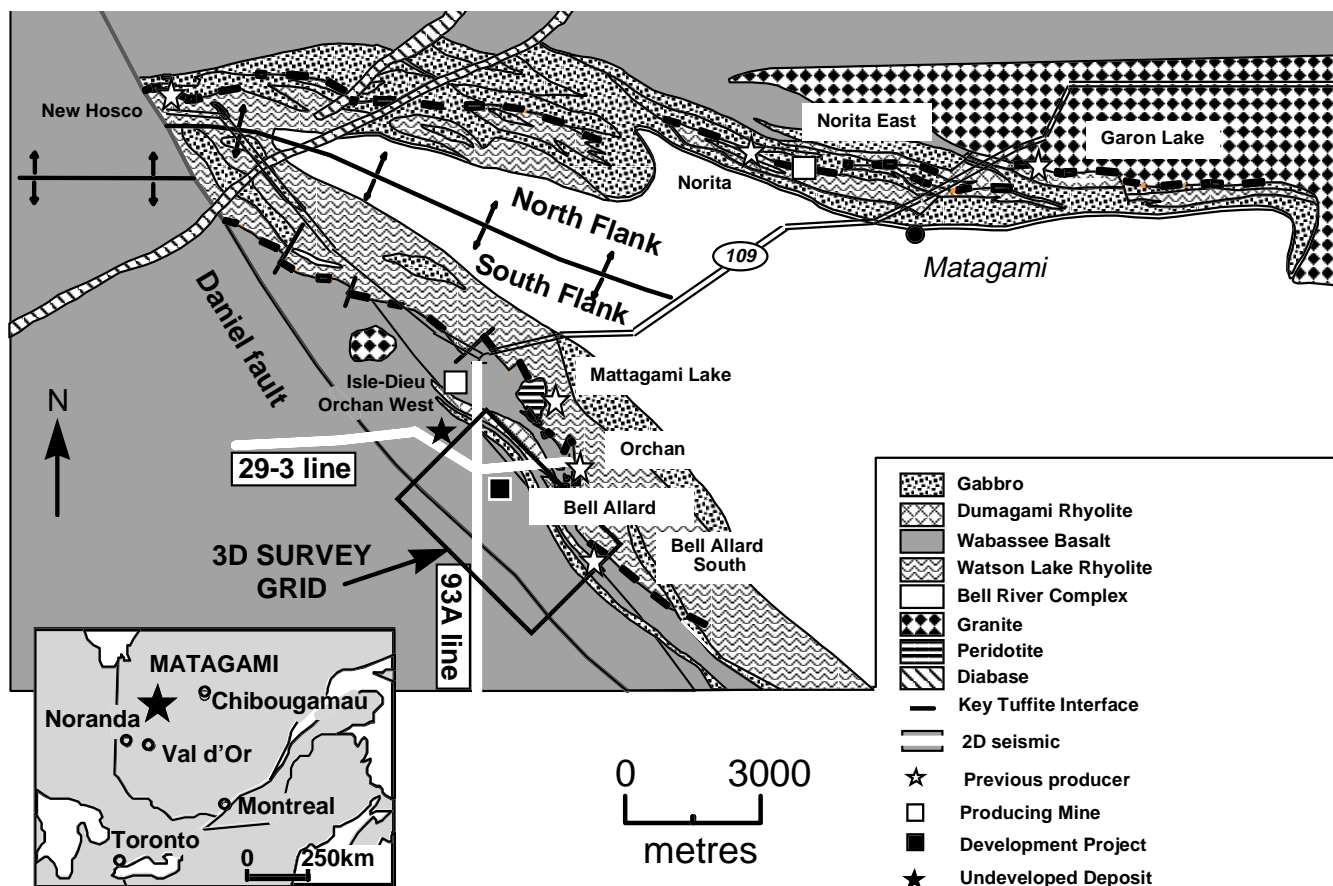


Figure 1: Geology and mineral deposits of the Matagami camp showing location 2-D seismic profiles and 3-D seismic survey area.

kilometres along strike and down-dip on the south flank of the mining camp (Sharpe, 1968). This thin horizon (0.6–6 m) was deposited during a period of intense hydrothermal circulation and represents the primary exploration target in the camp because it hosts most of the ore bodies discovered to date (Piché *et al.*, 1993). The Matagami volcanic complex is bounded to the south by immature volcanic-derived clastic sediments and iron formation of the Taibi Group across an important structural discontinuity, and to the north by the Matagami Group sediments composed mainly of siltstone and argillite with subordinate granitoid-pebble conglomerate (Beaudry and Gaucher, 1986).

The volcanic and sedimentary rocks were intruded during several episodes. The Bell River complex, which underlies and intrudes the Watson Lake Group, is a tholeiitic layered complex consisting of a layered sequence of gabbro with stratiform magmatic oxide concentrations, and finally capped by a felsic granophyric unit (Maier *et al.*, 1996; Beaudry and Gaucher, 1986). This intrusion is thought to be pre-tectonic and syn-volcanic in age and may have been the heat source for the hydrothermal activity observed within the overlying volcanic succession (Maier *et al.*, 1996; MacGeehan, 1978; Sharpe, 1968). A number of small, stock-shaped intrusions have been mapped along the south limb of the Galinée

anticline which range from ultramafic to felsic in composition (unpublished Noranda internal reports).

The volcanic rocks of the Matagami complex are folded into an open, gently northwest-plunging structure known as the Galinée anticline (Sharpe, 1968). Rocks on the south limb of the anticline, where the study area is located, are weakly deformed and metamorphosed, and dip approximately 45° to the southwest (Piché *et al.*, 1993). On the north limb the stratigraphy is subvertical and moderately to strongly metamorphosed, with the grade increasing from mid-greenschist facies in the west near the hinge zone of the Galinée anticline, to middle amphibolite facies east of the Bell River (Beaudry and Gaucher, 1986; Piché *et al.*, 1993). The north limb stratigraphy has been segmented into a number of distinct lozenge-shaped domains separated by coalescing deformation zones (Piché *et al.*, 1993). On the south limb, the Daniel reverse fault, a family of northwest-trending, moderately to steeply northeast dipping structures, has thrust the south limb stratigraphy and Bell River Complex over the Wabasseé Group volcanics (Piché *et al.*, 1993). Estimates of vertical displacement are variable, but may range in excess of 1,000 m across the structure (unpublished Noranda internal reports).

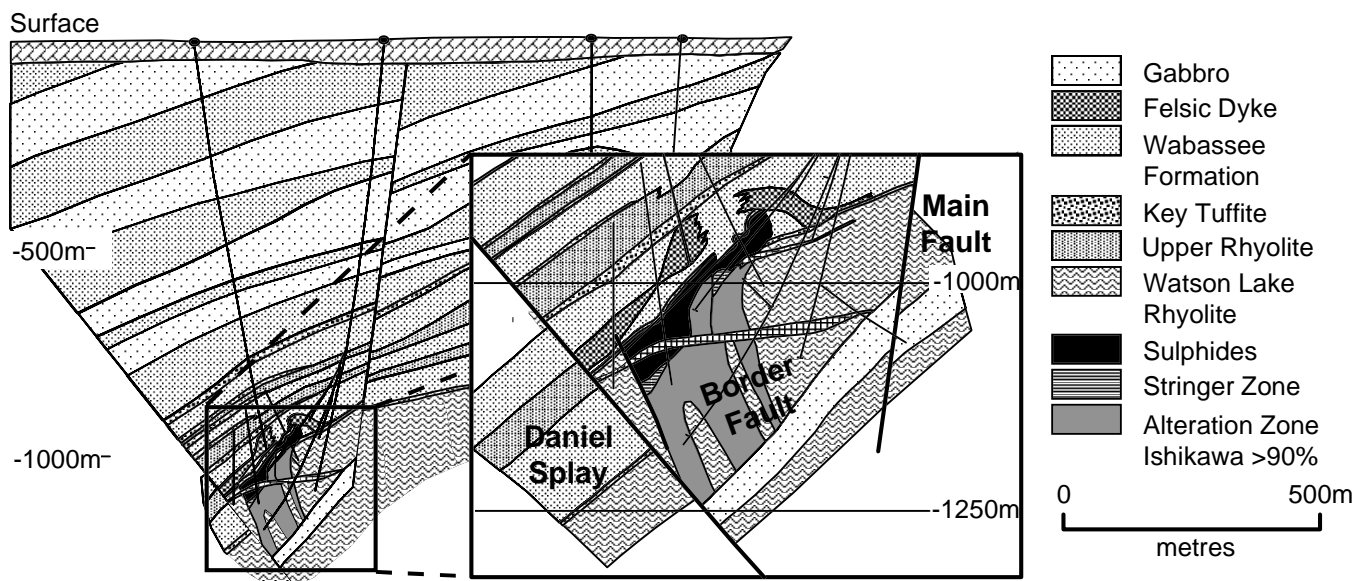


Figure 2: Vertical section through the Bell Allard deposit.

GENERAL DEPOSIT GEOLOGY

Bell Allard is a typical Matagami camp south flank VMS deposit. It is located at the Watson Lake-Wabasee interface atop a synvolcanic fracture zone, characterized by classic hydrothermal alteration. A weakly transposed concordant lens of sulphide mineralization directly overlies a discordant pipe, or conduit, hosting massive to stringer mineralization (Figure 2). The deposit is bounded to the south by a synvolcanic fault system (Boundary Fault) oriented 095° relative to north. The ore body consists of two lenses, and is approximately 370 m long and 165 m wide down dip along the Key Tuffite interface with an overall east-west orientation in plan. The north lens is composed primarily of high-grade Zn-rich massive sulphides while the south lens is of lower grade and comprised, in part, of conduit-type mineralization. Sulphide mineralization consists of pyrite, Fe-rich sphalerite, minor chalcopyrite and pyrrhotite. Thickness averages about 30 m, but can range up to 60 m in portions of the south lens. The deposit dips 50 to 55° towards the south between depths of 900 and 1150 m below the surface. A global resource in excess of 6 million tonnes makes Bell Allard the second largest deposit discovered in the Matagami mining camp. The 1994 production decision was based on a drill-indicated reserve of 3.2 million tonnes grading 13.77% Zn, 1.50% Cu, 43.45 g/t Ag and 0.76 g/t Au (unpublished Noranda internal reports).

PHYSICAL ROCK PROPERTIES

Physical rock properties of the main lithological units are summarized in Figure 3 by ellipses centred on the median density and P-wave velocity values, with axes that represent 1 standard deviation of the sample distribution (Adam *et al.*, 1996). Recent laboratory measurements by Salisbury *et al.* (1996) suggested that sulphides could be strong reflec-

tors. *In situ* and laboratory measurements were conducted to verify if these findings were applicable to the sulphides of the Matagami mining camp. P-wave velocities have been obtained from full waveform sonic logging data collected through 100 m of massive sulphides (borehole 94-26a) and laboratory density measurements were performed on split core samples. Laboratory density and P-wave velocity measurements were determined for seven core samples of massive and disseminated sulphides and three samples from a neighbouring mine (Isle-Dieu). Densities and P-wave velocities for pure sulphides and magnetite are shown for reference by the large dots. Lines of constant impedance (Z in Figure 3) are overlain to help estimate reflection coefficients between rock units. Reflection amplitudes are a function of the acoustic impedance contrast. For example, rhyolite in contact with a gabbro or a sulphide- and magnetite-rich lens will generate the strongest reflections. Figure 3 clearly shows that P-wave velocities and densities of the Bell Allard ore body contrast with those of the surrounding volcanic units. The highest impedance values are found for pyrite-rich samples while most of the volcanic rocks (95%) have impedances below 22. This suggests that there is a strong acoustic impedance contrast at the contact between Bell Allard and its host rocks. Pyrite and magnetite have the highest acoustic impedance values, hence these two non-economic marker minerals probably control the reflectivity of Bell Allard.

THREE-DIMENSIONAL FORWARD MODELLING OF BELL ALLARD

To obtain a better understanding of the seismic response of the Bell Allard ore body and to assist data interpretation, the 3-D zero-offset seismic response of Bell Allard was computed using the Born approximation (Beydoun and Mendes, 1989). The ore body appears as a complex diffractor with the highest amplitudes located west of the scattering

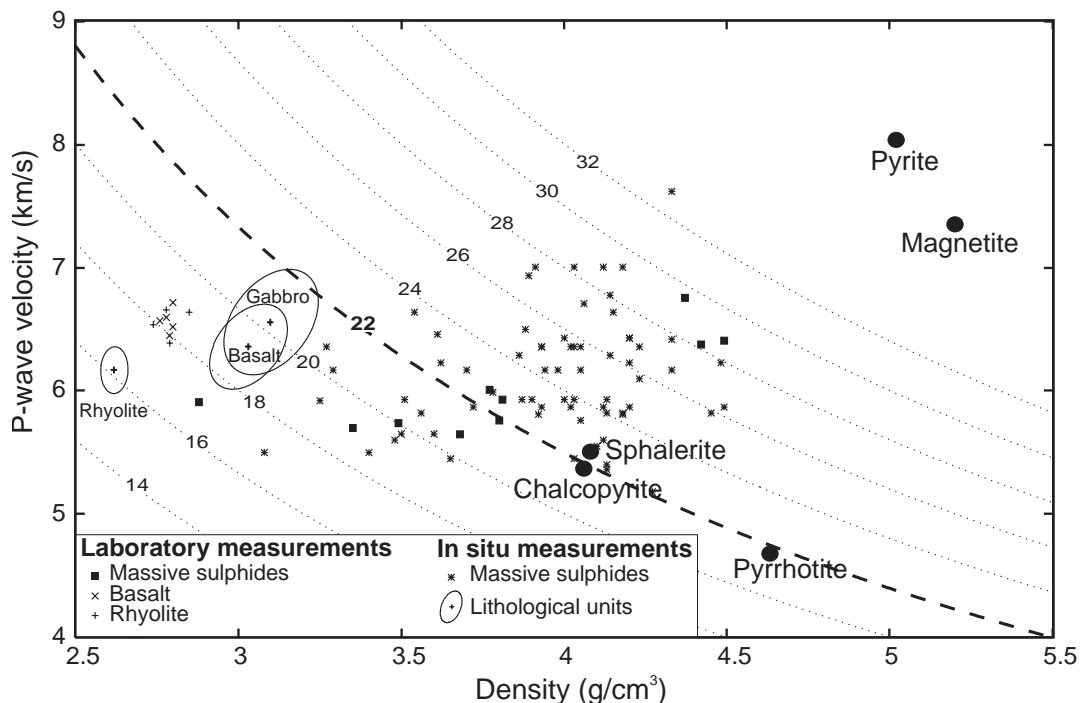


Figure 3: P-wave velocities and densities from logging hole 94-33f, and massive sulphides intersected in hole 94-26a. Laboratory data from core and samples from Bell Allard and Isle-Dieu ore bodies. Most volcanic units have acoustic impedances of less than 22 while sulphides have acoustic impedances above 22. Ellipses around lithologic units (gabbro, basalt, rhyolite) show 1 standard deviation of their sample distribution.

hyperbola apex. The modelling response also shows a phase reversal along a N-S line parallel to seismic profile 93A (Figure 1). This focusing of seismic energy appears to be caused by the tilted geometry of the deposit and by constructive interference between the top and bottom of the deposit. It is thus diagnostic of the overall attitude of the body.

The amplitude variation with offset of the diffraction from a dipping lens has important implications for data processing. The strongest reflected energy from a dipping lens is found at large source-receiver offsets and must be considered when muting first breaks or deciding on a normal moveout (NMO) stretch mute factor. For instance, diffractions from a 1-km deep dipping (45°) sulphide lens have high amplitudes at 1 km offsets that are subparallel to the first breaks. These can easily be mistaken for P-wave reverberations in the overburden. First break mute curves must be carefully designed; we had good success by setting the mute function based on accurate first break picks. Preserving the diffraction response from a dipping lens is a processing challenge, especially in a crystalline environment where the signal-to-noise ratio is low. A full prestack migration approach will effectively collapse the diffracted energy, but the characteristic variations of amplitude with offset associated with a dipping lens will be lost. Also, because of the phase reversal, migrating the data will reduce the anomalous amplitudes. Therefore, partial prestack migration techniques, such as DMO, are best suited to preserve the diffraction cone generated by an ore body. From the exploration point of view, the zero-offset stacked section is more appropriate to detect massive sulphide deposits because the conical diffraction pattern is larger, the amplitudes are stronger and the amplitude versus offset anomaly may provide information about lens geometry.

THREE-DIMENSIONAL SEISMIC DATA ACQUISITION AND PROCESSING

To confirm that seismic methods could detect the Bell Allard orebody *in situ*, 20 km² of 3-D seismic data were acquired above the Bell Allard deposit in April 1996 (see Figure 1). A total of 956 dynamite shots were recorded by up to 1900 receivers located along 19 receiver lines. Receiver groups consisted of a string of six geophones (10 Hz natural frequency) bunched together in a 1-m linear array. The recording time was 3 seconds using a sampling rate of 2 ms. A 164-Hz anti-alias filter was applied during data acquisition. Seismic surveys in the Matagami area are affected by highly variable overburden conditions. Thus, the most important processing step consists in the computation of an accurate refraction static solution. Data collected in the Matagami area is also characterised by low signal-to-noise ratios, making stacking critical to enhance the weak signal. Varying geological dip and the presence of seismic scatterers require that dip-moveout (DMO) corrections be applied to obtain a high-quality seismic image. The application of DMO corrections is simplified by a homogeneous velocity field with little lateral velocity variation. Scaling of the data was achieved by applying a spherical divergence correction (t^2) and a 3-s automatic gain control, thus preserving the relative amplitudes. The stacked data exhibit reflectivity from 600 m depth, providing good data quality at the target depth (1000 m). Figure 4 shows a migrated depth slice with clearly defined northwest-southeast-trending reflections. A more complex reflection pattern is observed east of the Key Tuffite.

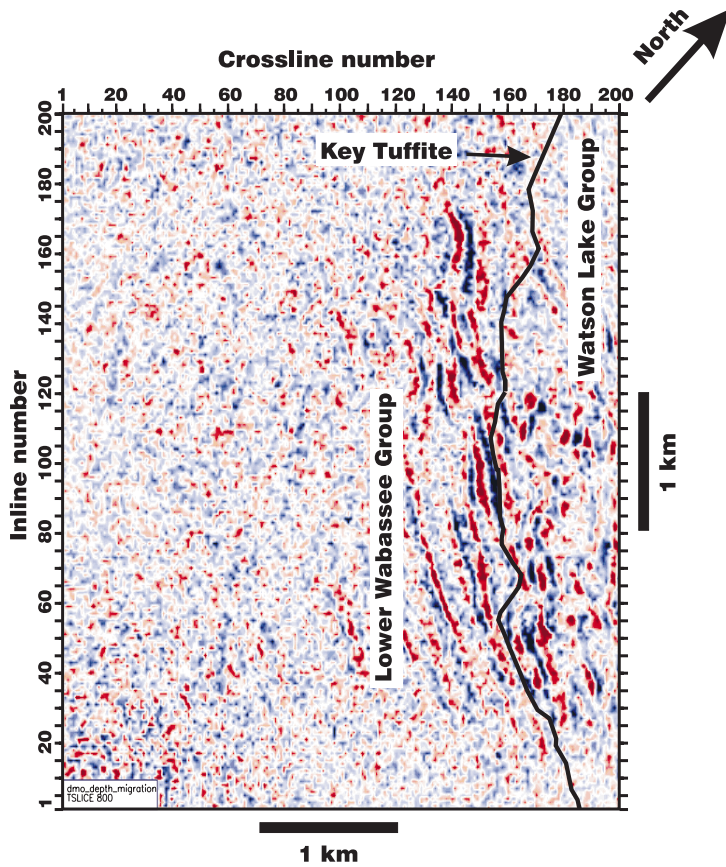


Figure 4: Depth slice showing continuous reflections, concordant with the Key Tuffite intersection from borehole data, between inlines 30 and 120. West of cross-line 160, the Watson Lake group shows undulating reflections that may be caused by gabbro sills.

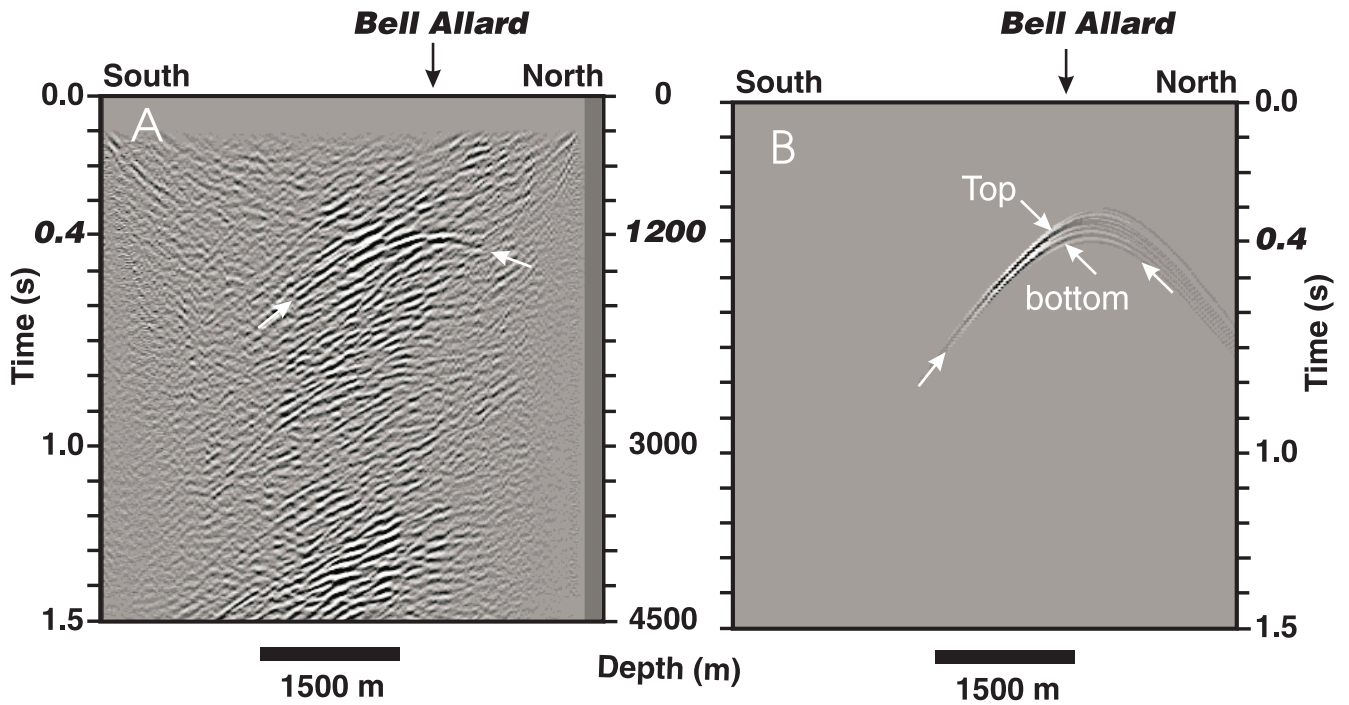


Figure 5: (a) Unmigrated north-south traverse along seismic profile 93A directly above the Bell Allard deposit. (b) Synthetic section modelled using Born approximation of same traverse.

PRELIMINARY INTERPRETATION

Imaging the Key Tuffite

The Key Tuffite horizon, gridded from borehole data, is in relatively good agreement with the seismic data (Figure 4), in particular to the south, where the 800-m contour follows very closely the reflection trend within the Lower Wabassee. In fact, between inlines 30 and 120 it seems that we can associate a seismic event with the Wabassee/Watson Lake Group contact, while north of inline 120, reflections are less continuous and the Lower Wabassee reflections are discordant with the Key Tuffite. Physical rock property studies (Adam *et al.*, 1996) have shown that the strongest reflections occur at rhyolite/gabbro contacts; thus we can speculate that the strong reflections within the Lower Wabassee are caused by rhyolite horizons that are discordant with the Key Tuffite. Reflectivity within the Watson Lake Group is clearly discordant with the Key Tuffite and is characterized by significant undulations, perhaps due to the presence of gabbro sills.

Seismic images of the Bell Allard deposit

Figure 5a shows an unmigrated section through the 3-D cube along a north-south traverse coincident with seismic profile 93A and directly above the Bell Allard deposit. The seismic section shows south-dipping reflections originating from rhyolite/gabbro contacts within the Lower Wabassee group, as well as a distinct diffraction hyperbola at the Bell Allard location. Note that the highest amplitudes occur on the southern flank of the hyperbola and that the same amplitude variations are observed on the synthetic section generated using the Born approximation (Figure 5b) (Eaton, 1996). The good match between the sections suggests that the response is due to the Bell Allard deposit. Since the upper part of the deposit is sphalerite-rich (low impedance) it is not reliably imaged and only the deep pyrite- and magnetite-rich zones appear to be reflective. This observation is in agreement with physical rock property studies which predicted that pyrite- and magnetite-rich ores have the highest acoustic impedances (Adam *et al.*, 1996; Salisbury *et al.*, 1996).

CONCLUSIONS

Seismic methods are effective at mapping subsurface stratigraphy in Matagami and can provide direct detection of massive sulphide deposits when conditions are appropriate. The seismic signature of the ore body depends of several factors: the seismic survey acquisition parameters, the geometry and size of the deposit, the ore zoning, and the impedance contrast between the ore and the host rocks must be significant. The physical rock property study shows that a strong impedance contrast exists between the deposit and the host rocks. Forward seismic modelling of Bell Allard predicted a characteristic seismic response, which was confirmed by the 3-D seismic survey. Also, on the south flank of the mining camp, units with contrasting acoustic impedances dip moderately to the southwest, allowing them to be mapped at great depths using seismic reflection methods. Overall, this region appears to offer good conditions for direct detection of ore and for deep structural and geological mapping using surface seismic methods.

3-D seismic surveys are relatively expensive (>Cdn \$50,000 per km²) yet are warranted as an alternative to deep stratigraphic-pattern drilling

to explore prospective horizons at depth within existing mining camps. More research is required to characterise the acoustic signature of massive sulphide bodies to distinguish such targets from other non-VMS-related features outlined by 3-D surveys. In addition, other survey designs must be investigated in order to lower the unit cost of seismic surveys, and thus shorten the period required to explore a particular area. With progress in these areas, seismic reflection technology could become a routine exploration method to test for deep ore bodies in VMS mining camps.

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Geological Survey of Canada contribution.

REFERENCES

- Adam, E., Milkereit, B., Arnold, G., and Pineault, R., 1996, Seismic response of the Bell Allard orebody, Matagami, Québec. Presented at the SEG Convention in Denver (1996).
- Beydoun, W.B., and Mendes, M., 1989, Elastic ray-Born l2 migration/inversion, *Geophy. J. Internat.*, 97, 151-160.
- Beaudry, C., and Gaucher, E., 1986, Cartographie géologique dans la région de Matagami. Ministère de l'Énergie et des Ressources du Québec, MB-86-32, 147 pages.
- Cinq-Mars, A., Mwenifumbo, C.J., and Killeen, P.G., 1995, Borehole geophysical logs from Lithoprobe project boreholes at Les Mines Selbaies and Lac Matagami, Québec. GSC Open File 2813.
- Eaton, D., 1996, BMOD3D: A program for three dimensionnal seismic modelling using the Born approximation. GSC OpenFile 3357.
- Lacroix, S., Simard, A., Pilote, P., and Dubé, L.-M., 1990, Regional geologic elements and mineral resources of the Harricana-Turgeon belt, Abitibi of NW Québec. *in* The Northwestern Québec Polymetallic Belt: A summary of 60 years of mining exploration. River, M., Verpaest, P., Gagnon, Y., Lulin, J.-M., and Simard, A., eds., Can. Inst. Min. and Met., Special vol. 43, pp.313-326.
- MacGeehan, P.J., 1978, The geochemistry of altered volcanic rocks at Matagami, Québec: A geothermal model for massive sulphide genesis. *Can. J. Earth Sci.*, Vol. 15, pp.551-570.
- Maier, W.D., Barnes, S.-J., and Pellet, T., 1996, The economic significance of the Bell River Complex, Abitibi subprovince, Québec. *Can. J. Earth Sci.*, vol. 33, pp.967-980.
- Piché, M., Guha, J., and Daigneault, R., 1993, Stratigraphic and structural aspects of the volcanic rocks of the Matagami mining camp, Québec: Implications for the Norita ore deposit: *Economic Geology*, 88, 1542-1558.
- Salisbury, M. H., Milkereit, B., and Bleeker, W., 1996, Seismic imaging of massive sulphide deposits Part 1: rock properties, *Economic Geology*, vol. 91. No. 5, pp.821-828.
- Sharpe, J. L., 1968, Geology and sulphide deposits of the Matagami area, Québec, Québec Department of Natrural Resources, Report 137, 122p, 8 maps.