Crosshole seismic investigations at Voisey's Bay, Canada

Enescu, N.[1], McDowell, G.M.[2], Cosma, C.[1] and Bell, C.[2]
[1]Vibrometric, Toronto, Ontario, Canada
[2]Inco Technical Services Limited, Copper Cliff, Ontario, Canada

Summary

Crosshole tomography is emerging as the most common geophysical technique for mapping sulphide distribution between drillholes. This paper describes the crosshole seismic investigations carried out in the Eastern Deeps deposit at Voisey's Bay, Labrador, Canada, in October and November, 1999. The Eastern Deeps deposit consists of troctolite-hosted disseminated to semi-massive sulphide (containing approximately 25%-75% sulphide) and an underlying massive sulphide zone.

A total of three pairs of diamond drillholes were surveyed in the Eastern Deeps deposit. The surveys were carried out in NQ diameter drillholes which were approximately 800-850 m in length. The holes were nearly vertical and hole-to-hole distances ranged from 45 m to 80 m.

The p-wave velocity tomography surveys were designed to outline the morphology and continuity of the massive sulphide zone. Confidence in the continuity of the massive sulphide zone is crucial since the relatively small massive zone contains a large portion of the metal in the Eastern Deeps deposit. Based on the results of these surveys, further sulphide delineation using surface exploration drillholes may be possible prior to underground exploration and development.

Introduction

Drill delineation of mineral deposits becomes increasingly costly with the increasing depth of the deposit. For delineating Ni-Cu sulphide mineralization, seismic and electromagnetic imaging methods can provide complementary geometrical information to drill data. A combination of core logging and geophysical data may offer an efficient and reliable way to infer the extent, shape, continuity and tenor of the ore. Core logs provide accurate data on the type and grade of the sulphide; however, gaining confidence by increasing the drillhole density can be costly and time consuming. Crosshole tomography is emerging as a viable geophysical technique for improving the delineation of sulphide bodies between drillholes.

Ground penetrating radar surveys find only limited applications for sulphide delineation due to the low penetration of electromagnetic waves through highly conductive sulphide mineralization. Lower frequency electromagnetic techniques, often referred to as Radio Imaging Methods (RIM), offer a larger range, but at the cost of lower resolution. Conversely, the penetration of seismic waves through hard rocks containing sulphide mineralization is relatively high and better resolved images of the rockmass can, in principle, be obtained using high frequency surveys.

In a related study, several drillholes in the Eastern Deeps deposit were logged with a full-waveform sonic tool and p-wave velocity as a function of depth was determined. This study indicated that the velocity of unmineralized host rock ranges from 5000 m/s to 6800 m/s, while the velocity of the massive sulphide zone ranges from 4000 m/s to 4500 m/s. Since the massive sulphide zone is anomalous in velocity compared to the host rock, crosshole seismic tomography is the technique of choice for delineation of this type of material.

The main obstacle to using crosshole seismic as a short-range ore delineation tool is the relatively slow rate of data acquisition. To make seismic surveys commercially practical, sources with a fast repetition rate and simultaneous recording of a large number of receivers is required.

Geology

The Voisey's Bay Ni-Cu-Co deposits are associated with Middle Proterozoic troctolite bodies that intrude Archean quartz-feldspar-biotite gneiss of the Nain Province as well as Early Proterozoic garnetiferous paragneiss (Tasiuyak Gneiss) of the Churchill Province.

The Voisey's Bay troctolite intrusions comprise two large bodies, one overlying the Eastern Deeps deposit and the other underlying the Reid Brook Zone and the Eastern Deeps deposit. A "feeder dyke" or "conduit" extends north of the Eastern Deeps as well as to the west through the area of the Ovoid, Discovery Hill Zone and Reid Brook Zone. This dyke appears to link the two troctolite bodies described above.

Immediately southeast of the Ovoid, the troctolite body overlying the Eastern Deeps broadens into a large intrusion with a steep, south-dipping, northern contact with the gneisses. The base of the troctolite body dips 25° southeast with a thickness of 400 m at its western margin, gradually thickening to about 1 km in the east. Its overall known width is approximately 1,500 m.

Crosshole Seismic, Voisey's Bay

A 30-50 m thick troctolite dyke extends northward from the main body of troctolite; this has been interpreted as a feeder for the main body of the troctolite and is believed to be the conduit through which the Eastern Deeps mineralization was transported.

The Eastern Deeps deposit occurs at the base of this intrusion, adjacent to the feeder, at depths between 650 m and 1,000 m. The deposit follows the base of the troctolite and dips uniformly to the southeast at approximately 20-30°.

Generally, massive sulphide occurs directly below the variable troctolite unit (a medium grained to pegmatitic troctolite to olivine gabbro containing partially digested gneissic fragments). Locally, there is an overlying unit of net-textured sulphides above the massive mineralization. The massive mineralization occurs as a single lens approximately 1.5 km in length, tapering towards the margins. Its maximum width is 200 m, but the average width is 100 m. The average thickness of the massive ore is approximately 20-30 m, however, thicknesses of up to 54 m exist.

More detailed geological information on Voisey's Bay can be found in the paper by Evans-Lamswood et al., 2000.

Crosshole measurements and instrumentation

The apparatus used at Voisey's Bay consists of a piezoelectric source based on the Swept Impact Seismic Technique (SIST) and a string of 24 hydrophones. The SIST system produces sweeps of seismic pulses, i.e. rapid sequences with a monotonically varying pulse rate. The idea of injecting energy over time is common to the techniques known as Vibroseis (Crawford, 1960), Mini-Sosie (Barbier, 1976) and SIST (Park, 1996, and Cosma, 2001). With Mini-Sosie, pulses are produced at pseudo random time intervals while with SIST, a monotonic variation of the impact frequency is used to produce a non-repeating impact sequence. The monotonic variation of frequency is a common element of the SIST and Vibroseis techniques. With Vibroseis, the frequency of the seismic signal is continuously varied. Conversely, with SIST, the frequency band of each impact remains essentially the same, while the frequency of the impacts is varied.

The Vibrometric SPH drillhole piezoelectric sources are designed for investigation ranges of up to several hundreds of meters and depths ranging in excess of 1000 m. The seismic signals are produced by applying high voltage to a stack of piezoelectric crystals. The frequency band is adjusted by using different numbers of piezoelectric stacks. The frequency band employed at Voisey's Bay was 100 - 3000 Hz. A sweep of approximately 1500 impacts was generated for each record.

The crosshole seismic measurements were performed in three vertical sections, from drillhole A (common to all three sections) to drillholes B, C and D. The measurements were conducted at depths varying from approximately 540 m to 770 m. The station increment was 0.5 m in the area judged as being of maximum interest and 1 m elsewhere, for both sources and receivers. A total of 16200 traces were recorded for each section.

Figure 1 and Figure 2 show an example of a seismic record and its frequency spectra. One can observe significant delays of the first onsets, due to propagation through regions of the rockmass with different seismic velocities, as well as tubewaves and P-S conversions occurring generally at the same depths as the travel time anomalies. The tubewaves accumulate below 400 Hz and the useful signal is concentrated in the 400 - 2800 Hz band. At depths where the signals display travel time anomalies the data is also anomalous in frequency.

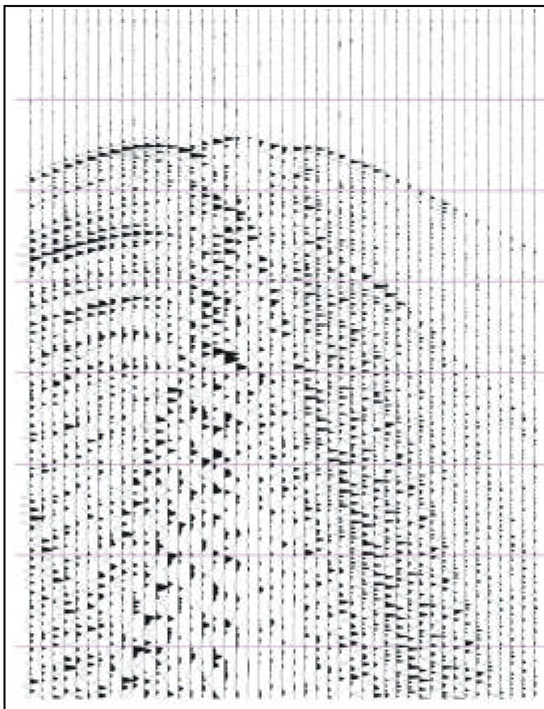

Figure 1: Receiver gather measured by the receiver located at a depth of 691.5 m in drillhole C.

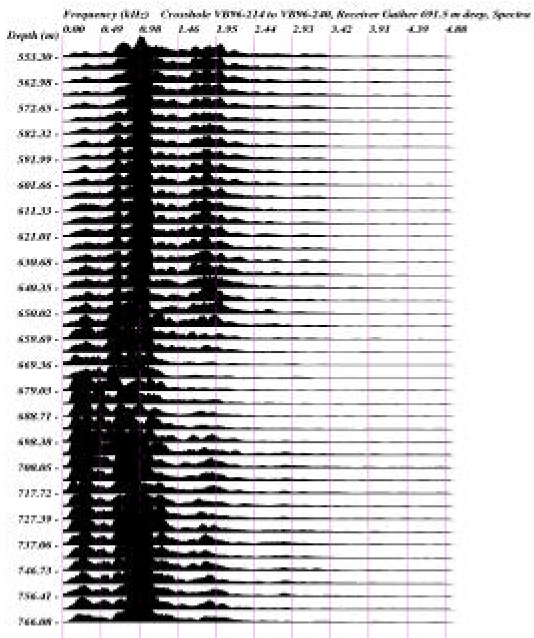

Figure 2: Frequency spectra of the receiver gather shown in Figure 1.

Tomographic reconstruction with positioning constraints

Source and receiver positioning errors can occur because of drillhole deviations that are unaccounted for and/or incorrect source and receiver depths. These are modeled as a series of geometrical transforms, which can be related to the common causes of a geometrical bias:

- translation of one drillhole with respect to the other, accounting e.g. for erroneous collar locations;
- rotation of the drillholes with respect to the collar positions, accounting for errors in determining the start azimuth of the drillholes;
- stretch along the drillholes, accounting for cable stretch and depth encoder calibration errors;
- drillhole bending, accounting for errors generated by incremental drillhole orientation determinations.

Figure 3 shows an example of the arrival time distribution for one of the seismic sections. The top view shows the arrival time plotted against the propagation distance and the bottom view shows the velocity plotted against the angle between the ray and the perpendicular to the drillhole. Both of these plots highlight geometrical errors related to drillhole and probe positioning. The effect of modifying the positions of drillholes and probes can be monitored by comparing the plots for different geometries. Large errors in positioning may be corrected in this way using a trial and error method.

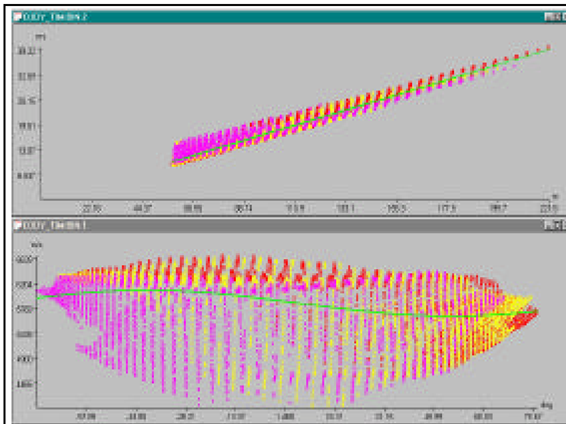

Figure 3: Two views of the arrival time distribution for the crosshole dataset. The top view shows the arrival time vs. the propagation distance and the bottom view shows the velocity vs. the ray angle.

To produce a resolved and reliable image, the crosshole tomographic method requires that the positions of the sources and receivers are determined very accurately. In practice, keeping the positioning errors to the level required by the tomographic method may prove to be a difficult task. With certain constraints applied, distance residuals can be generated while performing tomographic inversions and these residuals can be used to further correct the positions of the drillholes and the probes.

The tomographic process included the computing of curved ray paths. Several curved ray algorithms were tested and it was noted that the ray-tracing code must be stable throughout the iteration process, even if is not necessarily point-by-point accurate. A relatively slow converging algorithm was used (modified SIRT) to allow for the ray paths to stabilize between iterations.

Results

The p-wave velocity images representing the three seismic sections were generated from the first-onset data.

Figure 4 shows a 3-D view of the three crosshole seismic sections. The continuity of the low velocity, massive sulphide zone in the three panels is obvious. In addition, it is important that consideration be given to surveying a volume since out-of-plane effects can be significant. A high velocity zone located adjacent to the desired image plane can decrease the size of the anomalous zone located in the plane of interest. Combining 2-D planes to give a 3-D volumetric view will not eliminate this effect; however, it may highlight the presence of the high velocity zone.

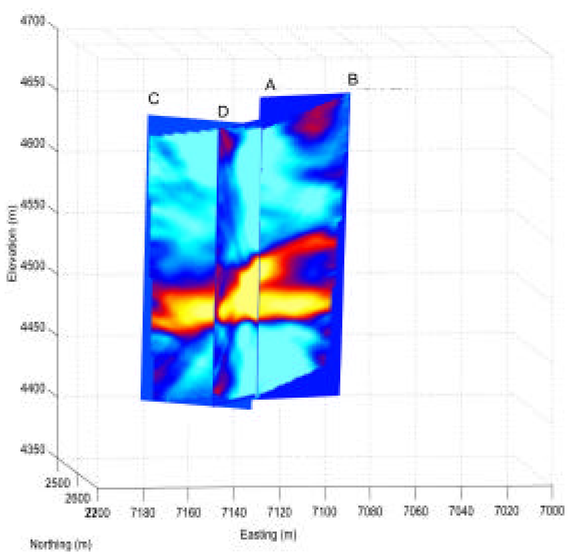

Figure 4: 3-D view of the velocity maps from the three crosshole sections.

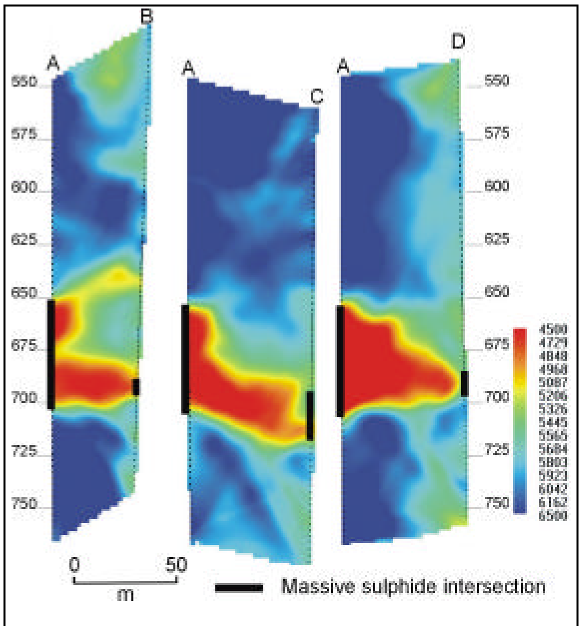

Figure 5: P-wave velocity field of the three sections determined by curved-ray inversion of the crosshole data.

Figure 5 shows the p-wave velocity field determined using curved ray inversion in the three panels. For reference, shown on drillholes A, B, C and D are the massive sulphide intersections. In general, there is good agreement between the intersections determined using the drillholes and the low velocity zones determined using seismic tomography. Integration of the drillhole velocity information will improve the correlation.

The seismic sections between drillholes A and C and between drillholes A and D indicated more massive sulphide between the drillholes than was modeled geologically. Future drilling will help determine the actual morphology.

Conclusions

Seismic tomography appears to detect massive sulphide zones reasonably well, but more work is needed to resolve the tenor of disseminated and semi-massive sulphide mineralization. With proper calibration it may be possible to differentiate between disseminated, semi-massive and massive sulphide.

An appropriate amount of crosshole seismic surveying may reduce the amount of drilling required in various stages of resource estimation. This may result in significant savings in exploration expenditures. Crosshole seismic surveys conducted from surface may also reduce the scope and cost of underground exploration programs.

References

Barbier, M.G., Bondon, P., Mellinger, R., Viallix, J.R., 1976. Mini-SOSIE for land seismology. Geophysical Prosp., 24, p. 518 – 527

Cosma C, Enescu N., 2001 Characterization of fractured rock in the vicinity of tunnels by the swept impact seismic technique. International journal of rock mechanics & Mining Sciences, 38(2001) p. 815-821

Crawford, J.M., Doty, W., and Lee, M.R., 1960. Continuous signal seismograph. Geophysics, 25, p. 95 – 105

Evans-Lamswood, D.M., Butt, D.P., Jackson, R.S., Lee, D.V., Muggridge, M.G., Wheeler, R.I. and Wilton, D.H.C., 2000. Physical controls associated with the distribution of sulfides in the Voisey's Bay Ni-Cu-Co deposit, Labrador. Economic Geology, 95, no. 4, p. 749-769

Park, C.B., Miller, R.D., Steeples, D.W. and Black, R.A., 1996. Swept Impact Seismic Technique (SIST). Geophysics, 61, no. 6, p. 1789 – 1803