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Cross-hole reflection seismic to delineate a relatively thin volcanogenic massive sulphide deposit in shale hosted environment

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SUMMARY

The seismic reflection method is a high resolution technique that can be used in many exploration environments including mineral exploration. However, mountainous terrain, depth of burial and the steepness of ore bearing structures pose a challenge to the application of surface seismic in mineral exploration. The cross-hole seismic method may present an alternative approach under such conditions. Presented here is a synthetic study examining the capability of the cross-hole seismic method to delineate a volcanogenic massive sulphide ore body in a shale hosted environment.

A simple model typical for volcanogenic massive deposits in Tasmania has been considered. There, an elongated steeply dipping volcanogenic massive sulphide deposit with an average thickness of 10 m is seated within a shale rock. The primary aim of the modelling is to test the capability of the technique to delineate relatively medium sized, steeply dipping volcanogenic massive sulphide lens in shale hosted environment. A second objective is to use the technique to prospect for extensions to mineralization along steeply dipping reflectors.

Synthetic cross-hole seismic records were generated using a 120 Hz energy source. Kirchhoff VSP migration was applied to wavefield separated shot records and Pre-stacked Depth Migrated images created. The resulting migrated images correlate well with the position and dip of the ore body demonstrating the potential of the cross-hole reflection technique to delineate steeply dipping ore structures in challenging environments.

Key words: Cross-hole, seismic, reflection.

INTRODUCTION

The exploration, discovery and subsequent development of volcanogenic massive sulphide (VMS) deposits are of great economic importance because of their polymetalic content. VMS deposits vary in size and shape : from elongated, regular, irregular and stratabound lens to stacked lenses and continuous tabular sheets (Hutchinson, 1973; Large, 1977; Solomon et al., 1987; Large et al., 2001; Galley et al., 2007). VMS deposits, like other massive sulphide deposits, are delineated mainly by electromagnetic (EM) methods, where there exists a substantial conductivity contrast between the host rock and mineralized zone. However, when located under deep cover, they cannot be properly resolved as the resolution capability of EM methods decreases with depth (Ford et al., 2006). The situation is made worse in conducting host rocks, especially clay related type, as the response from the host rock will mask out any response from the target (Telford et al., 1994; King, 2007). In such environment, acoustic contrast dependent techniques such as the reflected seismic methods may be applied to define the boundaries between the zone of interest and the host rock (King, 2007).

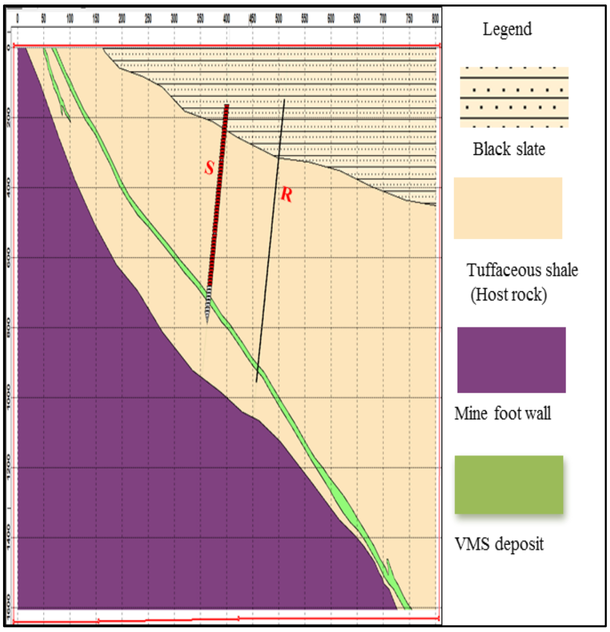
The reflection seismic method depends on acoustic impedance contrast that exists between the ore, the host rock and the country rock. Its resolution is dependent on seismic wavelength which, in turn, depends on the acoustic velocity of the host rock and the frequency of the seismic source (Salisbury et al., 2000; Eaton et al., 2003). Surface reflection seismic has high spatial resolution and applicable for structural and lithological mapping. But this method has a challenge to image sub-vertical and steeply dipping structures that are characteristic of hard rock environments because reflections from them are often not reflected towards the surface (King, 2007; Urosevic et al., 2012). In addition, the high frequency content of the seismic signal needed for higher resolution at depth is absorbed by thick, heterogeneous weathered layer. Furthermore, altered and highly fractured-zones cause significant scattering of seismic energy. This, in turn, produces complex seismic responses and highly variable reflection patterns, making seismic application challenging especially with surface seismic (Urosevic et al., 2007)

In Tasmania, the Southern section of the Rosebery types of VMS deposits are mostly buried under thick black slate and hosted within conducting tuffaceous shale. Sub-vertical and steeply dipping structures associated with the target are common (Solomon et al., 1987) and the area in general has varying topographical mountainous terrain and a dense cover of vegetation (Evans, 2009). Applying the reflection surface seismic is seemingly insurmountable.

We present the cross-hole seismic reflection method as an alternative approach that can potentially provide high resolution images in such a challenging environment.

METHOD

To test the capability of the cross-hole reflection method to delineate a VMS deposit hosted by thick and conducting shale, a simplified model resembling the southern section of the Tasmania Rosebery mine has been considered. This is shown in Figure 1. The tuffaceous shale host rock is placed between the underlying mine foot wall sequence and the overlying black slate. We considered a scenario typical of an elongated steeply dipping VMS deposit found in this section of the Rosebery mine. A deposit of an average thickness of 10 m, having a geologic dip of about 60 degrees, is located close to the surface and extends several metres down-plunge. Two angular boreholes, S and R, approximately 110 m apart were used as source and receiver boreholes respectively. The source borehole was populated with source stations at 10 m interval whereas the receiver borehole was populated with receiver stations at 5 m. Acoustic properties assigned to the various layers are as shown in Table 1.



S - source borehole **R** – receiver borehole

Figure 1. A synthetic geologic cross-section resembling part of the generalized East-West Southern section of the Rosebery mine. Shown also are the source and the receiver boreholes.

(Note: The cross-section is not drawn to scale). Simplified from: Tasmanian Geological Survey Bulletin 72; Solomon et al. (1987).

Acoustic full-waveform modelling was performed using a Ricker wavelet with 120 Hz dominant frequency, a sampling rate of 0.4 ms and record length of 300 ms. Synthetic seismograms and wave propagation time snaps were generated. Time snaps were used to understand the propagation pattern of the P-wave energy in the model. The wavefield propagation and synthetic seismic section for shot point 25 are shown in Figure 2. The figure identifies the different up- and down-going wavefields generated. Trace editing was used to restrict offsets. Trace muting, 2d spatial filtering and f-k filters were applied in the wavefield separation to remove the direct and surface reflected down-going waves and other unwarranted waves. Thus, only the reflected up-going waves (and their multiples) were preserved. Figure 3 shows a section of the resulted seismograms after the wavefield separation. VSP Kirchhoff migration (Dillon, 1985) was then performed on the wavefield separated seismograms to generate depth seismic profiles. The host rock velocity of 4525 ms^{-1} was used for the migrations. The migration image space between the boreholes, for case 1, was 370 to 460 m to a depth of 1000 m while that for the extension to mineralization, case 2, was 100 to 400 m by 1000 m depth. Within the range considered, the best result migration aperture for the two cases was 25 and the migration was focused to image at 60^0 dip.

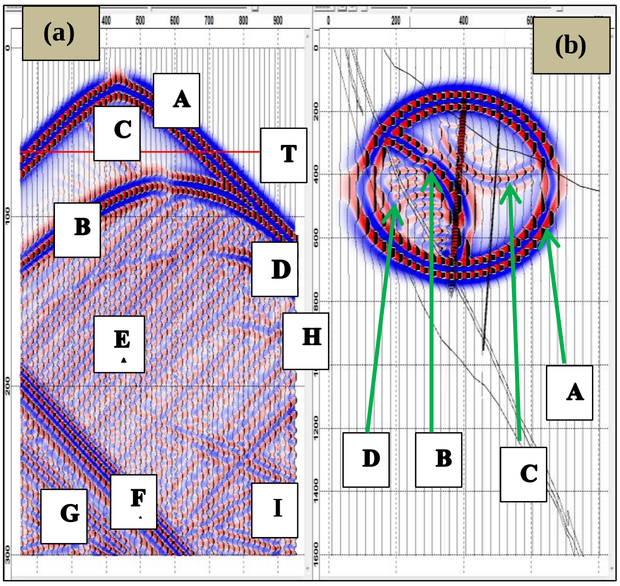
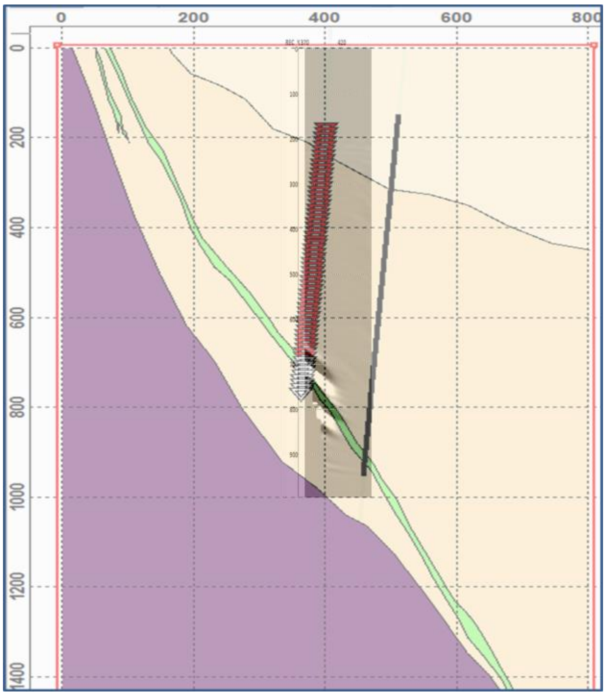


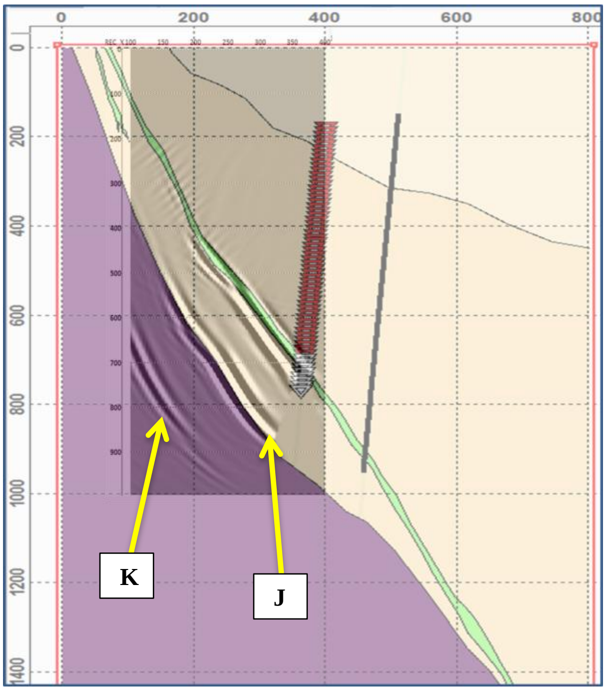
Figure 2. The synthetic seismogram (a) for source point 25 and the corresponding wave propagation animation (b) showing some of the primary and multiple wavefields: A – direct wave; B – up-going reflection from the up-dip side of the target zone (out of the boreholes); C – down-going reflection from the black slate caused by the up-going event A; D – up-going reflection (multiple) from that part of the Mine foot wall not in line with the boreholes (this has almost the same pattern as event B and it took place just below the occurrence point of event B); E – overlap of up-going reflection from target zone lying between and outside the boreholes and some multiples including those from the Mine foot wall; F – down-going reflected multiples from the surface due to event A; G - down-going reflected multiples from the surface due to events B and D and other up-going waves; H – some multiples caused by the interactions of the up-going and down-going waves from up-dip side of the boreholes between the deposit and the foot wall sequence and started being recorded by the bottom receivers below the target zone; I – some up-going reflected multiples from down-going parts of events A, B, D and H; T – time step line.

RESULTS

Figure 4 (a) and (b) show the Pre-stack depth migrated, PSDM, images of the VMS deposit within the migration constrains, for case 1 and 2 respectively. Both images are overlaid by the geologic section. The deposit has not been illuminated very much between the boreholes. The portion of the deposit that has been imaged was up to about 430 m lateral extent from the source borehole. Illumination of the up-dip side, the extension to mineralization, is just the opposite case as it has well been illuminated. Both images map the depth and dip of the deposit and contoured the VM sulphide lens. Artefacts occurred in both images. This may be partly due to the multiple reflections. Conspicuously, the Mine foot wall contact with the host rock is imaged, indicated J, in Figure 4 (b). This is due to the strong reflection from the Mine foot wall, indicated as event D on the synthetic seismogram, Figure 2. Similarly, image K is due to event H in Figure 2. These unwanted images can be corrected through further processing. In all, the depth to the VMS deposit as well as its dip has been accurately determined.



(a) Migrated image of the deposit obtained between the boreholes overlaid by the geologic section.



(b) The migrated image obtained up-dip as an extension to ore deposit overlaid by the geologic section.

Figure 4. The resultant images obtained in the two cases superimposed by the geologic section in each case.

CONCLUSIONS

A model typical for VMS deposits in Tasmania has been created. The cross-hole seismic reflection method has been tested to delineate ore body between the boreholes and to prospect for extension(s) to mineralization. The PSDM images show that, the technique has the potential to delineate dipping VMS ore body structures in a shale hosted environment. The cross-hole seismic reflection technique is capable of delineating steep dipping structure(s) once reflections emanate from the structure to the receivers. Thus, unlike cross-hole seismic tomography, imaging is not limited to within the boreholes but the technique can be used to prospect for mineralization extensions along even steep dipping reflectors.

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Rock type	P-wave velocity (ms^{-1})	Density (kgm^{-3})
Black slate	4430	2600
Tuffaceous shale (host rock)	4525	2429
Mine foot wall	6425	2825
Volcanogenic massive sulphide deposit	5240	5850

Table 1. Estimated P-wave velocities and densities assigned to the various rock layers in the model, Figure 1.
Sources of the physical properties: Telford et al. (1994); Eaton et al., Hardrock Seismic Exploration (2003); Andrew Alden, (Densities of common Rock Types), About.com, Open File.

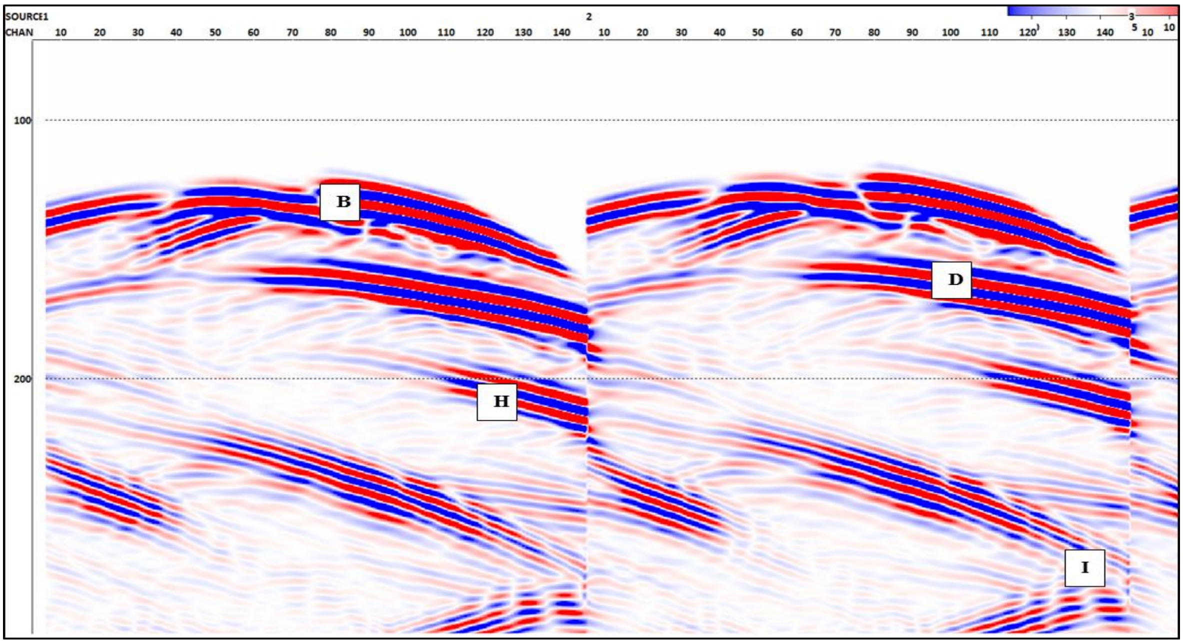

Figure 3. A section of the synthetic shot records, in colour scale, after the wavefield separation. Events B, D, H and I represent similar events as shown in Figure 2. On the migrated section, Figure 4 (b), event H has been imaged and indicated as K and D as J. The image of the target zone came from event B.