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Detection of sulphide bodies in seismically scattering environments: a modelling study

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ABSTRACT

A severe limitation to seismic exploration in the mining industry comes from the environments that host most deposits: hardrock media tend to scatter large amounts of energy, resulting in recorded seismograms with potentially very poor signal to noise ratios. In addition to this fundamental problem is our lack of understanding of how localized targets scatter/reflect seismic energy, and how to adapt acquisition and processing parameters to heterogeneous, hardrock environments and mining targets. In this paper we present the results of a numerical modelling study of heterogeneity and scattering, and the detection of massive sulphide deposits in hardrock media. We incorporate all available information, including compressional as well as shear velocities, into our elastic modeling. We categorize scattering environments as seismically transparent or reflective (noisy) depending on the ratio of seismic source frequency to the dominant scale of heterogeneity. This heterogeneity and the resulting noise in seismic data can vary significantly depending on the area, making certain places unfavorable to seismic exploration. Models of scattering media with varying scale lengths demonstrate the difference between favorable and unfavorable seismic exploration environments: when the ratio of scale length to seismic wavelength is ~1, large amounts of scattering noise are generated that reduce the S/N of surface recorded data. By adjusting seismic acquisition parameters it is possible that a poor S/N can be improved. When simple bodies representing sulphide deposits are placed in these models, they are detected provided that 1) the deposit has a large enough impedance contrast, 2) it is larger than the dominant seismic wavelength, and 3) its dimensions are either *smaller or greater than the dominant scale of heterogeneity of the host rocks. When these criteria were met, a coherent reflection from the orebody was detected in all models. Known AVO responses are however altered depending on the background heterogeneity.*

INTRODUCTION

3D seismic surveying is now well established in the petroleum industry as an essential tool for exploration. In the mining world however, seismic surveying is used primarily for mine planning and development purposes, it has yet to be proven efficient and cost effective for exploration. In Canada, tests of 2D and 3D reflection seismic surveying have met with varying success: low signal to noise (S/N) ratios and a lack of prominent marker horizons require that interpreters move from a more traditional approach of mapping structure and lithological contacts where mineralization is known to accumulate, to one of identifying "bright spots" for possible orebody identification (see the Matagami and Val d'Or projects - Adam et al., 2003; Adam et al., 2004). This new approach requires an understanding of how localized targets scatter or reflect seismic energy, in particular when they are embedded within a heterogeneous and possibly strongly scattering medium.

Seismic scattering is a fundamental problem for hardrock exploration; it can introduce varying amounts of noise into recorded seismograms depending on how heterogeneous the environment is, a characteristic defined by a scale length that relates to the fluctuations in physical properties of the material. This scale length can range from the very small (related to cracks, porosity and thin layering) to the very large (continental scale lithology), and defines a propagation regime that governs seismic scattering (Wu, 1989). We thus have three main regimes to consider when developing seismic models: 1) the quasi-homogeneous regime, where the scale of scatterers (a) is much smaller than the seismic wavelength (λ), 2) the large-angle regime where a is comparable to λ, and 3) the small-angle regime, where a is much larger than λ. In the large-angle regime, seismic energy is scattered at large angles from the incident direction (i.e. back to surface), whereas in the small-angle regime most scattered energy is directed forward.

Motivation

A common target for Canadian hardrock exploration programs is massive sulphides. Recent case studies have shown that these sulphides, with their relatively high densities, provide more than the required impedance contrasts in typical host rocks to produce

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strong reflections of seismic waves (Salisbury et al., 2003). Numerical modeling also shows that pure mineral sulphide bodies can have characteristic responses depending on their shape, size and composition (Bohlen et al., 2003; Eaton, 1999), including offset and azimuthal trends that may be critical in interpreting seismic datasets (Milkereit et al., 2004).

Realistically however, these deposits are embedded within heterogeneous backgrounds, where perturbations in densities (ρ), compressional (Vp) and shear (Vs) velocities can be as high as 10%. Depending on the scale length of this heterogeneity and the scattering regime considered, S/N ratios may not be high enough to accurately capture the response from a localized sulphide target (L'Heureux, 2006).

The modeling study described in this paper investigates the conditions under which seismic reflection methods could be used as a tool for exploration in the mining industry. To understand scattering effects we first include models of various ideal targets embedded within backgrounds of varying scale lengths. A more realistic case is then developed that represents a more complex sulphide target. The parameters used to develop the petrophysical models are estimated from log data from the Sudbury impact structure, Ontario, Canada. The structure is host to numerous sulphide deposits which have accumulated at the base of the melt sheet formed during impact (Sudbury Igneous Complex – SIC), as well as within the footwall below.

PETROPHYSICAL MODELS

Six basic models were developed and run with an elastic finite difference (FD) code (Bohlen, 2002). The models are 1000m wide by 2000m deep, with an average P-velocity, S-velocity and density of 6000m/s, 3800m/s and 2850kg/m^3 respectively. The stochastic fluctuations were generated with a von Karman autocovariance distribution, defined by a given scale length (see Frankel and Clayton, 1986, for example). The isotropic models have scale lengths in the horizontal and vertical directions of 1m for the quasi-homogeneous model, 20m for the large-angle model and 1000m for the small-angle model. Two additional anisotropic models have vertical scales of 10m and horizontal scales of 100m (a_x/a_z = 10) and 1000m (a_x/a_z = 100) (figure 1). Two reference targets were added to each of the models at 1600m depth with the properties of a sphalerite/chalcopyrite mixed orebody (density of 4100kg/m^3, Vp and Vs of 5300 and 2800m/s). The spherical target has a diameter of 200m and the elliptical target a major axis of 400m and minor axis of 30m.

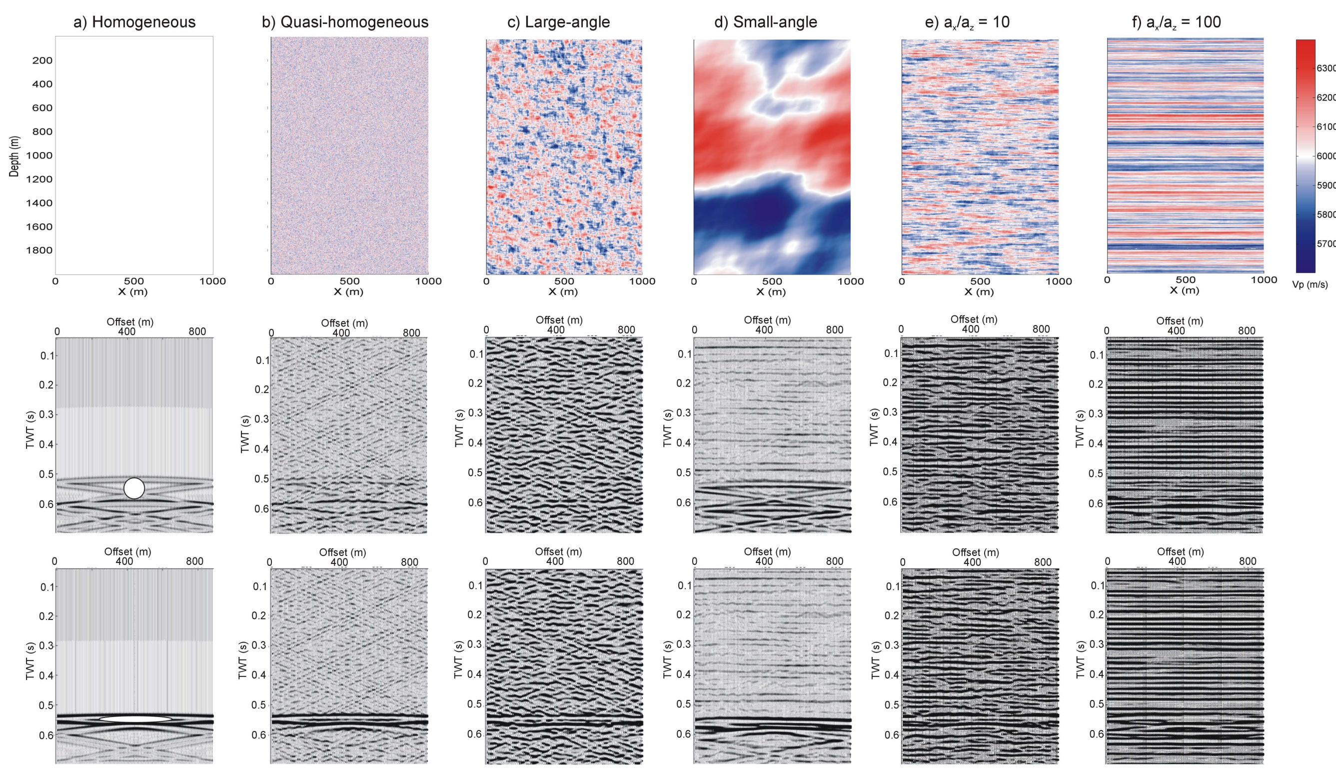

Figure 1: top row: petrophysical models representing the various scattering regimes (Vp represented). a) quasi-homogeneous, a_x=a_z=1m, b) large-angle, a_x=a_z=20m, c) small-angle, a_x=a_z=1000m, d) a_x/a_z=10, e) a_x/a_z=100. Second row: vertical component synthetic seismograms for each model, including spherical sulphide target. Bottom row: vertical component synthetic seismograms for each model, including ellipsoidal sulphide target. Note that all seismograms are scaled equally.

The source function used in each of the models was a plane wave impulse in the vertical direction with a frequency of 50Hz (wavelength ~120m). The quality factor Q, defining the ratio of peak seismic energy to energy dissipated through absorption, is high in each of the models so that any attenuation observed is due to scattering. Receivers were placed along the surface with an 8m spacing. The FD code computes the total wavefield at each grid point, then extracts horizontal, vertical, compressional and shear components.

RESULTS

Figure 1 shows the vertical component synthetic seismograms for each of the petrophysical models. Scattering from background heterogeneity produces increasing amounts of noise from the quasi-homogeneous to the large-angle regimes, while in the small-angle regime minimal scattered noise is generated but travel-time and amplitude anomalies are introduced into the transmitted wavefront. The response from the spherical target is only distinguishable from background noise when heterogeneity scale lengths are either smaller or larger than the size of the target (Figures 1b and d). However, in the small-angle regime the target response suffers a traveltime delay of ~2% (L'Heureux, 2006), and shows anomalies in its amplitude. When the aspect ratio of the target is increased, the deposit is detectable in the isotropic models (Figures 1 b to d) and is less distinguishable from the scattered noise in the anisotropic models (Figures 1 e and f).

DISCUSSION

The six models of Figure 1 demonstrate one of the main issues involved in using seismic datasets for mineral exploration. A good understanding of the heterogeneity of the host environment, as well as suspected orebody characteristics, is necessary before a seismic survey can be planned. The scale of heterogeneity may dictate acquisition parameters such as source frequencies that are necessary to avoid any "noisy" scattering regimes. While vertical scale lengths may be easily derived from petrophysical log data by autocovariance analysis (see for example Holliger et al., 1996; Holliger, 1996), horizontal scales are more difficult to determine. If there is a lack of correlation between two or more borehole logs, such as is the case for Sudbury, an existing seismic dataset may be used to infer the extent of correlated reflected energy, and hence horizontal scale length (see L'Heureux and Milkereit, 2007 for example). Using detailed geological maps provides an indirect method for determining horizontal values, however can typically be applied only at a regional scale (Holliger and Levander, 1994).

Background influence

Bohlen et al. (2003) showed that the seismic response of a simple lens orebody in a homogeneous background will exhibit an amplitude variation with offset (AVO) specific to the composition of the body (for bodies with the properties of gabbro, sphalerite, galena and pyrite). Given the travel-time and amplitude anomalies observed for the small-angle regime model above, we wished to investigate whether background scattering has an effect on these trends. Four new models were therefore generated, with a sphalerite lens at the depths of 600m and 1200m in two small-angle backgrounds. The two backgrounds are generated by different (random) distributions of physical properties. The model orebody has a long axis of 130m, short axis of 50m, is centered at x=800m and dips to the right in the model by 35°. Identical acquisition setups were used in all models: an explosive source configuration was used (ricker wavelet, center frequency of 50Hz, position x=1000m), with receivers placed every 8m along the surface.

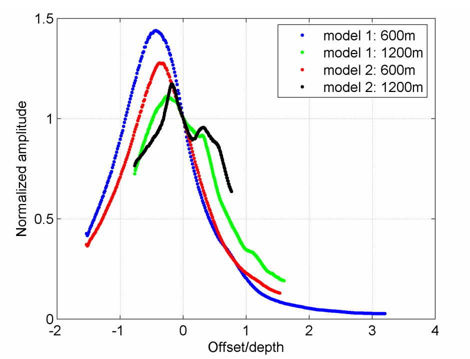

Figure 2: Plot of amplitudes for lens bodies in a small-angle medium, normalized to the 0-offset trace and to model orebody depth. Compare green and black lines together (depth=1200m), and red and blue lines together (depth=600m). Note that the overall amplitudes of the deeper bodies (green and black) are much smaller than the shallow bodies.

Figure 2 shows the amplitude response from the sphalerite lenses, normalized to the 0-offset trace. To compensate for the difference in depth of the lenses, the offset response is taken with respect to orebody depth. The shape of the bodies has a focusing effect in the negative offset direction: the largest amplitudes received by surface seismometers are observed directly above the lens' position. However, the overall offset response of the bodies at 600m depth (red, blue) are not identical, especially in the negative offset direction. The targets at 1200m (green, black) show largely anomalous variations as the incident and reflected wavefronts become more affected by the random fluctuations of the background. An overall trend is difficult to identify. This suggests that in the small-angle regime different offset trends may be observed depending on the depth of the body, and that for the same depth, different background fluctuations will result in a different recorded amplitude response. This could lead to a misinterpretation with respect to the composition of a mineralized target, if AVO trends are to be relied upon. Ideally, before interpreting such responses from real targets, the scattering nature of the medium under investigation should be known.

Sudbury model

The Sudbury structure is of primary importance in Canada for sulphide mining, but presents a unique setting for seismic exploration. Its two main lithologies, the SIC and footwall, possess different heterogeneity characteristics and average physical properties. Several borehole logs from the structure show that the footwall is characterized by small scale lengths (< 10m, L'Heureux and Milkereit, 2007), relatively high compressional and shear velocities of ~6400 and 3800 m/s respectively, and an average density of 2900 kg/m^3. The SIC on the other hand has scale lengths on the order of 100m, Vp ≈ 6100m/s, Vs ≈ 3800 m/s and ρ ≈ 2800 kg/m^3.

A final model was generated that represents the above characteristics for Sudbury. The model has the above physical properties, a dipping contact between the SIC and basement, and a sulphide target within the footwall (figure 3). The dipping contact is picked from a 3D seismic dataset at the western edge of the Sudbury basin, and the orebody properties from average sample values (representing a pyrrhotite/chalcopyrite mixed ore). With the above properties, and a source frequency of 60Hz, the model represents both the small-angle scattering regime (in the SIC) and the large-angle regime (in the footwall).

Three main events can be identified in the resulting shot record (vertical component seismogram) (figure 4): The compressional and shear wave reflections from the SIC/footwall contact, and the P-P orebody reflection at ~0.45s. The shear reflection from the orebody follows outside the recording range at ~0.8s. The deposit's reflection is distinguishable from background noise as a series of short reflectors, whereas the contact events are coherent over most of the section. A section from the 3D seismic dataset at Sudbury shows comparable features to the model (Figure 5); the migrated data show bright localized reflections in areas of known sulphide deposits, while the contact is observable as a change in reflective character between the SIC and footwall.

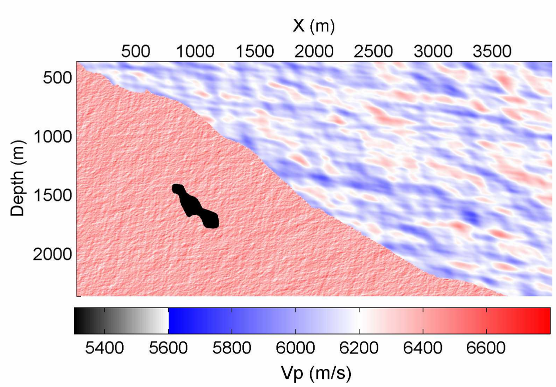

Figure 3: Sudbury model. The upper medium (SIC) is in the small-angle regime while the lower is large-angle. A mixed orebody (pyrrhotite/chalcopyrite) is placed in the footwall.

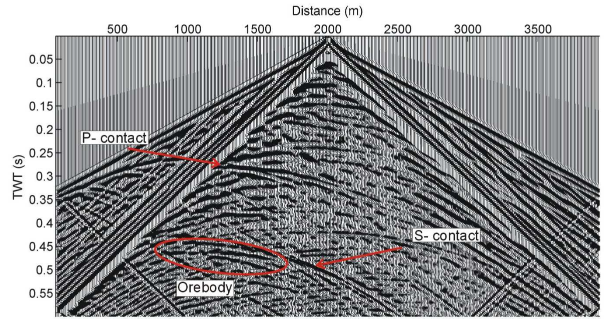

Figure 4: shot record of the Sudbury model, showing a reflection from the SIC/footwall contact (~0.3s) and scattered orebody response (~0.45s).

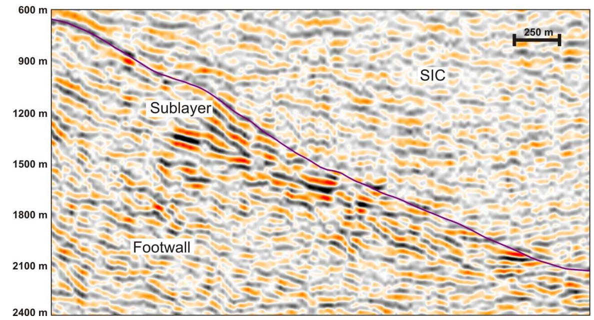

Figure 5: migrated seismic section from the Sudbury 3D seismic survey. The sublayer is host to many sulphide deposits, which give rise to bright reflections in the migrated data.

CONCLUSION

Given that for mineral exploration the targets are typically considered as scatterers themselves, the realistic seismic response of a massive sulphide target depends on both its size relative to background heterogeneity as well as its impedance contrast. Encouraging results indicating that these orebodies exhibit characteristic responses depending on their shape, size and composition are tempered by the fact that background fluctuations in physical properties may alter recorded amplitudes.

Seismic methods for hardrock exploration have not yet seen their full potential. Typical acquisition and processing schemes for large-scale continental surveys or for sedimentary basin exploration have not seen much success for shallow crystalline environments; these traditional techniques need to be adapted to the sometimes highly scattering environments that host mineral deposits. To do this we need to assess how heterogeneous the medium is, something that can be done easily with petrophysical log data. Acquisition parameters such as source frequencies need to be adapted to survey within the scattering regime that will produce the least amount of noise, but consideration has to be given to the target and its response within the heterogeneous hosting material.

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