3D Seismic Imaging for Mineral Exploration

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Introduction
For more than 70 years, reflection seismic methods have been used with great success to explore sedimentary basins for hydrocarbons. Some problems associated with the application of seismic profiling in the hardrock environment for mineral exploration differ from those encountered in sedimentary environments (Milkereit and Eaton, 1998). In the 1970-ties and 80-ties, many tests of high-resolution seismic imaging methods for mineral exploration have had only limited success. Recently, however, 3-D seismic imaging techniques are used where a fully comprehensive prospect evaluation is desired or where mine planning issues need to be addressed (Eaton et al., 2003).

Early Applications and Recent Developments

Controlled source seismic methods for mineral exploration - a few key milestones:

1908 Mintrop used a falling weight (4 to) and the first portable seismographs to study seismic wave propagation - the beginning of controlled source seismology.

1914 Fessenden filed a patent (method and apparatus for locating ore bodies) - the first seismic application to mineral exploration.

1980 Ties seismic imaging of shallow sedimentary hosted mineral deposits (Wright, 1981); first high-resolution seismic images from faults and fractures in the hardrock environment (Green and Mair, 1983), an application to rad-waste studies in the Canadian Shield.

1987 Exploration'87. First successful application of 2D seismic profiling in a mining camp (Pretorius et al., 1989).

1993 MITEC review of reflection seismic surveying for mineral exploration applications (Reed, 1993), led to comprehensive petrophysical, borehole geophysical and seismic studies of massive sulfides (Milkereit et al., 1996).

1994 First 3-D seismic survey for mineral exploration, a case history from South Africa (Hall and deWet, 1994) - about 22 year after the foundation of 3-D seismics (Walton, 1972). The first 3D seismic survey for Ni-Cu exploration was conducted in the Sudbury basin in 1995 (Milkereit et al., 2000).

1997 Exploration'97, first successful application of 3D seismics for mine planning and development (Pretorius et al., 1997) following an approach to cost-benefit evaluation of 3D seismics used in hydrocarbon exploration (Aylor, 1995).

2002 From exploration to mine planning and development. Duweke et al. (2002) present high-resolution 3D seismic images from the Bushveld Complex.

Reflection and Scattering

The average velocities of the common crystalline rocks tend to increase with density along the well known Nafe-Drake curve for silicate rocks. Thus, velocities and densities tend to increase as the rocks become more mafic and increase in metamorphic grade. Because of their high densities, sulfides lie far to the right of the Nafe-Drake curve within a large velocity-density field controlled by the end-member properties of the minerals pyrite (Py), pyrrhotite (Po), chalcopyrite (Cpy) and sphalerite (Sph). The sulfide field can be further divided into sub-fields in which the velocities and densities are controlled by simple mixing lines between the properties of the end-member sulfides and their silicate hosts. Thus, rocks composed of a mix of pyrite and felsic host rocks increase in velocity with increasing density. On the other hand, ores composed of chalcopyrite, sphalerite or pyrrhotite plus associated host material actually *decrease* in velocity with increasing density, while $V_P \sim$ v3V_S for many rocks, several important rock types depart significantly form this pattern. In particular, quartz-rich rocks have anomalously high shear wave velocities while mafic rocks often display anomalously low S-wave velocities. Both V_P and V_S are unusually high for pyrite compared to most other sulfide minerals, causing many common mixed sulfides to have high impedances for both P waves and S waves.

Since an impedance difference of at least 2.5 x 10^5 g/cm^{2}s is required to give a reflection, most mafic rocks (Z ~ 20 g/cm^{2}s) can give strong reflections when in contact with felsic rocks (a finding confirmed by many reflection surveys) and fresh ultramafic rocks will reflect against any lithology. Similarly, if the deposit meets the geometric conditions for detection many sulfide ores should make strong P-wave reflectors against most common silicate rocks. Does this mean that the search for "bright spots" is an appropriate direct seismic exploration tool for orebodies, analogous to early efforts at direct detection of gas sands in the 1970's? To seek answers to this question, we must turn to numerical simulations of elastic-wave interactions with ore deposits, in the context of realistic geological models.

Even for deposits that originally formed in sedimentary environments, orebodies rarely occur in a simple stratigraphic setting, or for that matter in any simple sheet-like form. There are, of course, exceptions (including conglomerate-hosted gold deposits and layered ultramafic intrusions in southern Africa), but for the most part orebodies are characterized by a complex shape and spatial dimensions that are comparable to (or smaller than) the Fresnel zone associated with the source frequencies used and deposit depth. Ore deposits thus generally fall within the so-called Mie scattering regime, and common tools-of-the trade such as ray tracing are probably not the best choice for predicting their seismic expression. Recent modeling studies based on the Born approximation (Eaton, 1999) have shown that the shape of ore deposits may exert a first-order control on their P-wave scattering response. Unlike point diffractors or spherical bodies, dipping lenticular or ellipsoidal inclusions appear to focus scattered P waves in the specular direction, down-dip from the orebody. Finite-difference modeling (Bohlen et al., 2003) has provided additional insight on orebody scattering phenomena. Figure 1 shows a finite-difference snapshot of P waves scattered from a single inclusion designed to approximate the size, shape and composition of the recently discovered Bell Allard South Zn-Cu orebody in northern Quebec. High-amplitude backscattered signals propagate almost horizontally away from the deposit, at a near-specular scattering angle with respect to the incident ray (dashed line).

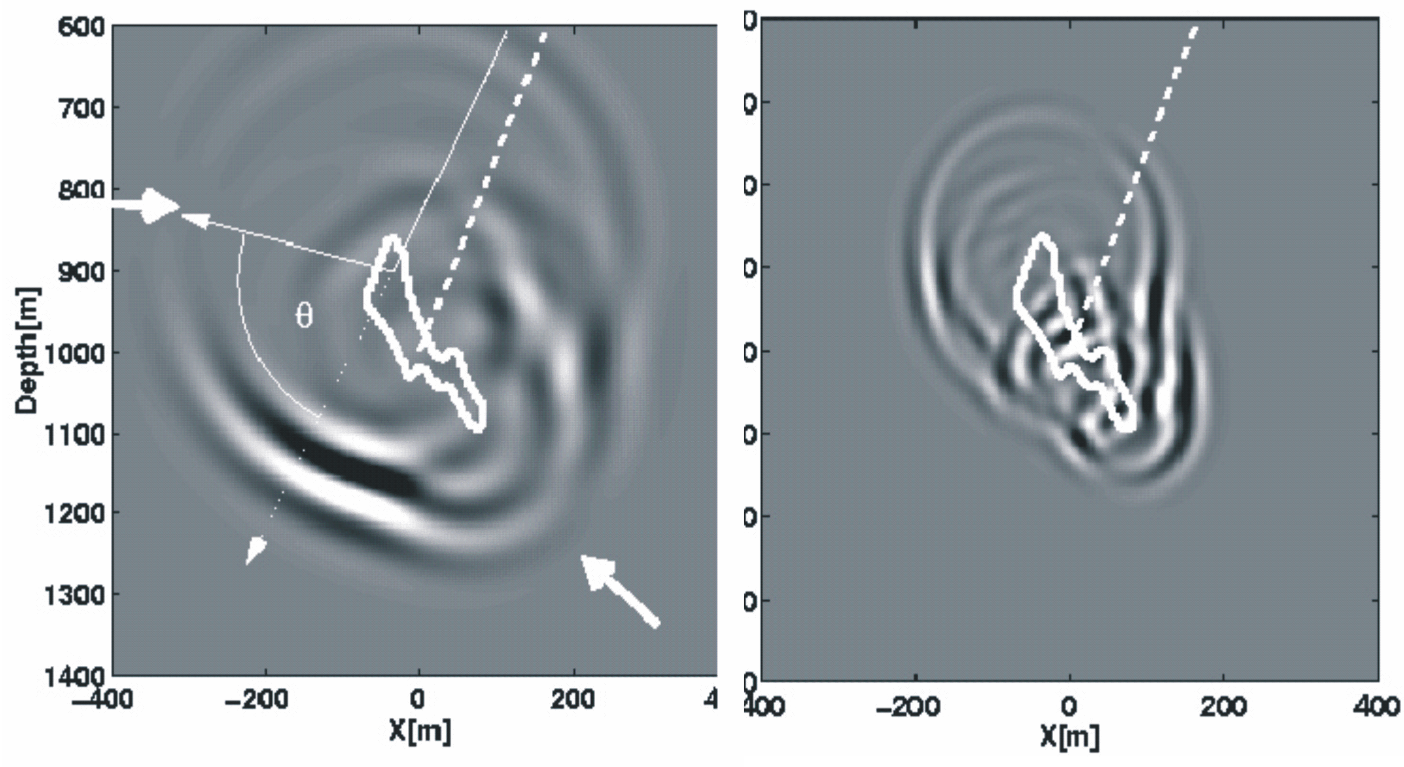

Figure 1. Finite-difference snapshot of scattered P (left) and S (right) waves for a homogeneous background medium of intermediate composition (*Vp* = 6 km/s) containing a sphalerite inclusion. The shape of the inclusion is modelled after the Bell Allard south orebody in northern Quebec. The dashed line indicates the incident ray direction. Note the single phase reversal (large white arrow) occurring at a scattering angle of approximately 76 degrees. Modified from Bohlen et al. (2003).

3D Seismic Imaging – Recommendations based on case histories

Encouraging results from North America, southern Africa, Scandinavia and Australia show that modern digital recording equipment – including “off-the-shelf” seismic sources and geophones – do not require special adaptation for most mineral-exploration environments. Typical data characteristics, including low SNR, discontinuous reflections, and complex scattering effects, can be overcome by careful data acquisition, processing, forward modeling and interpretation. Some considerations that have emerged from recent studies include:

- Ore deposits are generally characterized by anomalous elastic properties, especially density. Nevertheless, comprehensive knowledge of physical properties, including density, P- and S-wave velocity, is essential for robust interpretation of seismic data for mineral exploration. In previously unexplored areas, laboratory physical rock property studies and borehole logging are an essential prerequisite to seismic exploration.

- Forward modeling studies provide an important basis for survey design and interpretation of field data. In general, economic ore deposits have length scales similar to seismic wavelengths and thus fall within the Mie scattering regime, impying that approximations based on small scattering bodies (Rayleigh scattering) or Snell’s Law ray tracing are not valid. Accurate forward modeling using a fully elastic algorithm (e.g., 3-D finite-difference) and a physical properties database is necessary to understand seismic scattering response of an ore deposit.

- In geological terranes where steep dips prevail, downhole seismic imaging methods provide a way to image features around an existing borehole.

- In the case of surface profiles or 3-D surveys, high-fold, broadband datasets are essential. Traditional rules-of-thumb for minimum fold, as applied to data acquisition in more familiar settings, must be revised and amended. As a result of the relatively high seismic velocities that prevail in hardrock environments, higher-than-normal source frequencies (> 100 Hz) are needed to ensure adquate resolution of the targest of interest.

- Data processing tends to be more costly and time consuming than often anticipated. Key data procesing steps include statics (refraction and residual), prestack noise attenuation, surface-consistent deconvolution and pre-stack migration.

As expensive 3D seismic surveys must provide information for both exploration and mine planning, we have seen a move towards high-frequency seismic surveys in the hardrock environment over the past 10 years. A good example is a recent 3D seismic survey with frequencies up to 200 Hz from the Bushveld Complex in South Africa (Duweke et al., 2002). In the future, high-frequency 3-D seismic imaging techniques will be increasingly used where a fully comprehensive prospect evaluation is desired, or where deep mine planning issues need to be addressed.

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