What can seismic in hard rocks do for you?

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SUMMARY

As the search for mineral deposits moves to greater depths, seismic methods, with its penetration ability and unmatched resolution power, are becoming more important tool for exploration of mineral resources underneath the deep cover. However the performance of seismic appears to be still inconsistent which prevents it from becoming the primary exploration method in the mineral sector, similar to its role in oil exploration. The performance of seismic methods is affected by complex geology, excessive ambient noise, access restriction, weak reflectivity and/or low signal to noise ratio, limited acquisition program due to cost restriction, etc. Two other factors are emerging recently as important: a) lack of correlation of seismic images and b) miss-match between survey design and target characteristics. The first one is the greatest threat to the affirmation of seismic in the mineral sector as it prevents seismic images to be utilised in any constructive way. The second one translates to the use of simplified 2D geometries to delineate complex 3D structures which may cause seismic to underperform. On the positive side there are clearly favourable cases for the application of reflection seismic. Those can be primarily related to the massive, concentrated mineralisation such are massive sulphides.

The less favourable geological settings require much more elaborate analysis to allow seismic method to perform. It appears that the lack of understanding of the complexity and the variability of seismic responses in different geological settings is what still prevents the widespread use of this method for mineral exploration. In general seismic could be useful in different ways, from regional to deposit scale and from exploration to production stage.

INTRODUCTION

Potential field methods are traditionally and successfully used in mineral exploration to delineate potential mineralised zones and also discover resources at shallower depths. However, the only method that can provide high definition images of the underground and has required depth of penetration is seismic reflection method. The potential of the method has been realised early but the outcomes were sometimes below the expectations. From many case histories examined it appears that there are some common errors that effectively slowed down the development and the application of seismic methods for exploration of mineral deposits. These "common errors" can be attributed to inadequate survey parameters, inappropriate processing steps and lack of communication between service provider and mini geologists. Furthermore, the "rule of thumb" transferred from oil industry to the application of seismic for minerals exploration often produced poor results, adding to the failed attempts cases.

Seismic reflection method has achieved spectacular results in oil and gas exploration during past decades. In fact seismic methods, in various forms, have been used in oil exploration for the last 70 years (Milkereit and Eaton, 1998). Despite such remarkable success of the seismic reflection method in soft rock environments, the mining industry has been reluctant to embrace this technology primarily because, until recently, its needs could have been met by potential field methods (electromagnetic, induced-polarization, gravity). Additional reasons include very high cost of the seismic methods and their variable performance in hard rock environments. However as discovery of large near-surface deposits is becoming increasingly rare and the known reserves of most economic minerals are in decline, it is clear that new deep exploration techniques such are seismic methods are required to meet the future needs of industry (Salisbury and Snyder, 2007, Malehmir et al., 2012).

Mineral deposits are found in geologically older regions where the subsurface structures have typically been subjected to folding, shearing, metamorphism and other effects. These subsurface forms are therefore much more deformed and may not be revealed by the wavelengths produced using a traditional seismic survey. Additionally, the minerals of interest often generate a seismic signature that may be hard to distinguish from the surrounding material. In fact the difference in acoustic impedance (velocity-density product) between the deposit and surrounding rocks, and its geometry will basically determine whether or not a potential reflector can be detected and imaged by seismic reflection techniques (Salisbury and Snyder, 2007). If conditions are met, the success however is not guaranteed. To image excessively complex 3D geology that often host mineral deposits is challenging. Specific acquisition approach (target illumination), processing techniques (time and depth wave field extrapolation and image construction) and interpretation (seismic attributes, inversion and visualisation) are needed.

EARLY APPLICATIONS OF HARD ROCK SEISMIC

In western countries, in the 1970-ties and 80-ties, many tests of high-resolution seismic imaging methods for mineral exploration had been conducted. One of early exploration works includes seismic imaging of shallow sedimentary hosted mineral deposits (Wright, 1981). First high-resolution seismic images from faults and fractures in a hard rock environment were presented in Green and Mair (1983), an application to red-waste studies in the Canadian Shield in 1987. High seismic activity for mineral exploration was recorded in 80's in South Africa (Pretorius et al., 1989).

In the eastern European countries, mainly Russia (USSR at the time), hard rock seismic was rather widespread. One of the earliest seismic surveys in a hard rock environment was carried out in 1927 to investigate ore deposits near Krivoi Rog (Karaev and Rabinovich, 2002). In the 1940s the correlation refraction seismic technology was used to study the crystalline basement (Gamburtsev et al., 1952). The high-frequency seismic method was for the first time attempted in mid 50's to investigate ore deposits and map vertical-layered media (Berson, 1957).

Despite these early works it took about 22 year after the foundation of 3-D reflection seismic method (Walton, 1972), for the first 3-D seismic survey for mineral exploration to be conducted in South Africa (Hall and deWet, 1994). Subsequently, 3D seismic survey for Ni-Cu exploration was conducted in the Sudbury basin in 1995 (Milkereit et al., 2000) and Pretorius et al. (1997) who conducted the first successful application of 3D seismic for mine planning and development.

SEISMIC EXPLORATION IN AUSTRALIA

After sporadic trials in Australia in mid-seventies, Geoscience Australia collected in 1990s several province scale seismic traverses throughout the Eastern Goldfields (Drummond et al, 2000). These sections provided exciting new information about major structures in the province, and stimulated new ideas about why the big gold deposits occur where they do.
The application of seismic methods at a mine scale really took off only in the early 2000. This relatively slow start in the application of seismic for mining was followed by a rapid increase in mine scale, particularly 3D seismic surveys. Present distribution (most of it) of regional scale (lines) and mine scale (circles) seismic surveys is shown Figure 1.

Figure 1. Seismic surveys conducted across Australia.

Distribution of mine scale seismic across the globe is shown in Figure 2. It is clear that the highest number of mine scale 3D surveys is conducted in Australia. After a number of failed starts over several decades, it looks like hard rock seismic is finally here.

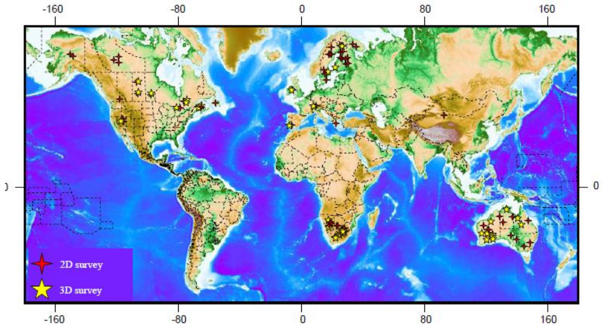

Figure 2. Seismic surveys conducted across the world. The highest density of 3D seismic surveys is found in Australia (Malehmir et al., 2012).

SEISMIC AT DIFFERENT SCALES

The methodology is there, but the each situation has its own complexity. This can be explored and delineated at different scales. A regional seismic line ~(250K long) recorded over Olympic dam by Geoscience Australia (GA) in 2003 is shown. Large number of mega structures and shears, nicely expressed dominates the image. A sedimentary area to the east can clearly be identified. An enlarged portion, some 20 km, of the same line is shown in Figure 4

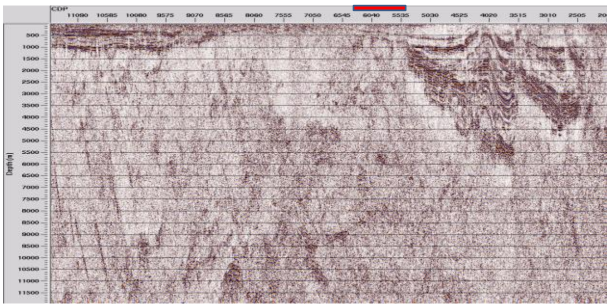

Figure 3. Regional seismic line 03GA-OD1 recorded by GA over Gawler craton in 2003. The area marked with the red bar on top of the display is shown in Figure 4.

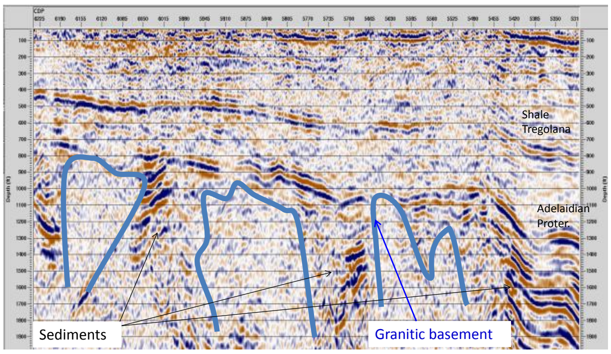

Figure 4. Enlarged portion of the line showing a distinctive difference between intrusives and sediments. It is clear from this image how to plan exploration drilling.

Going from 20 Km scale to 200 m scale we find that seismic can perform equally well (Figure 5).

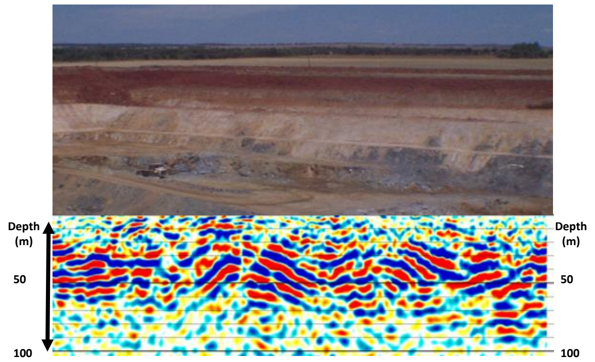

Figure 5. Ultra-high resolution seismic acquired of talk deposit at Three Springs (Urosevic et al., 2002).

Across to Yilgarn craton we also find that reflection seismic performs well at all scales. At regional scale seismic images can be matched well with the potential field maps (Urosevic and Stolz, 2006). This is shown in Figure 6. At very fine scale high-resolution seismic may be used for targeting gold deposits associated with fine structures (Figure 7).

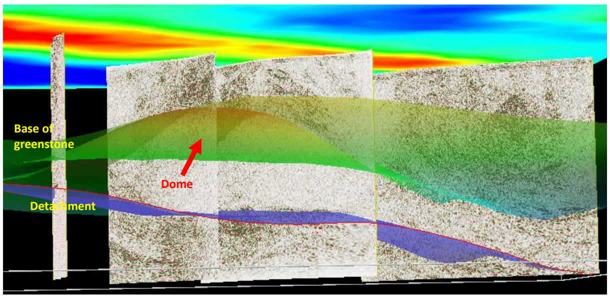

Figure 6. Seismic lines across St Ives mining camp.

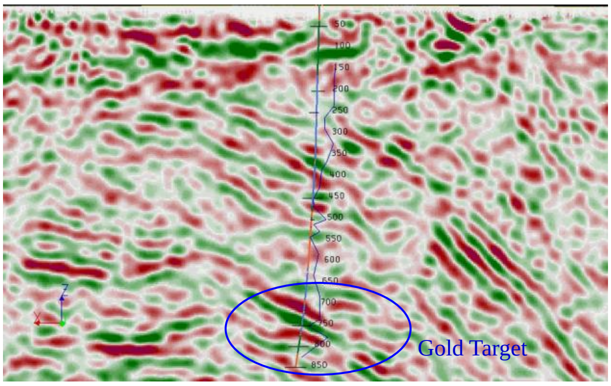

Figure 7. High resolution seismic survey over St Ives ground highlighting the mining targe and its potential extension that can be easily tracked across seismic section (Urosevic et al, 2007).

SEISMIC RESPONSE OVER VARIOUS GEOLOGICAL SETTINGS

Different geological setting can have vastly different seismic signatures. In ultramafic/basalt setting such as found in Kambalda, WA, a prolific gold and nickel producing region, the reflectivity of shears, intrusives and massive ore bodies (to a lesser extent) are nicely expressed. High quality seismic images are often recorded in Kambalda region due to favourable geological conditions and also near surface conditions. In particular the source/receiver coupling across the salt lake Le Froy produces exceptional quality seismic images. For that reason even small size massive sulphide bodies which only show modest reflectivity in contact with host rocks can still be detected by surface seismic (Urosevic et al., 2012). In Figure 8, it can be seen that Kambalda VMS deposits are low on the reflectivity scale in comparison to Canada or Europe. Moreover the massive ore is concentrated in much smaller volumes than typically found in Canada and Europe. Still due to exceptional quality of seismic images and and the application of volumetric interpretation, direct targeting of nickel ore was made possible (Figure 9).

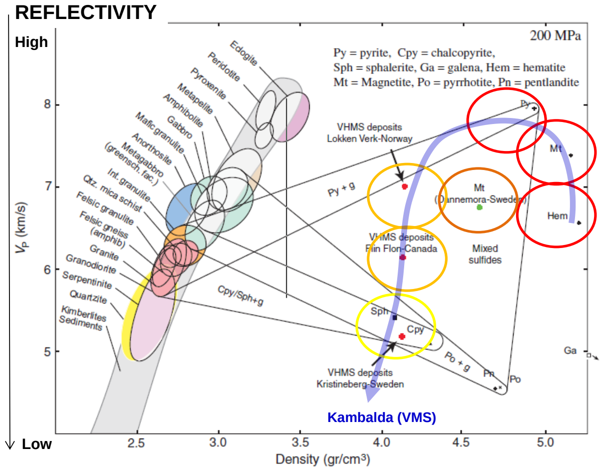

Figure 8. Elastic parameters of VHMS and VMS deposits (modified from Salisbury et al, 2003).

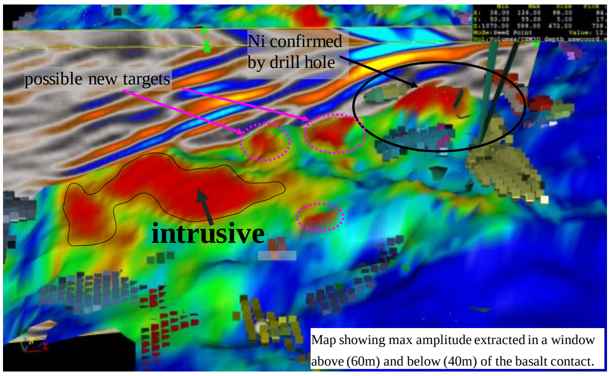

Figure 9. Small pockets of massive ore detected by high resolution, high quality 3D surface seismic recorded over salt lake.

In the same region, but away from the salt lake the quality of seismic images is still high and permits specialised analysis. Moving to the shallower depths,(up to 500 m, we can use seismic images for mapping fine structures and alterations that are likely to host gold. In this case various seismic attributes or their combination appear to be useful as long as a high quality well tie can be established. Such an example is shown in Figure 10, where instantaneous seismic attributes and recovered acoustic impedance were combined to highlight the alteration zones hosting gold mineralisation (Harrison and Urosevic, 2008). Such analysis can only be done after calibration of seismic by borehole logs (Full Waveform Sonic).

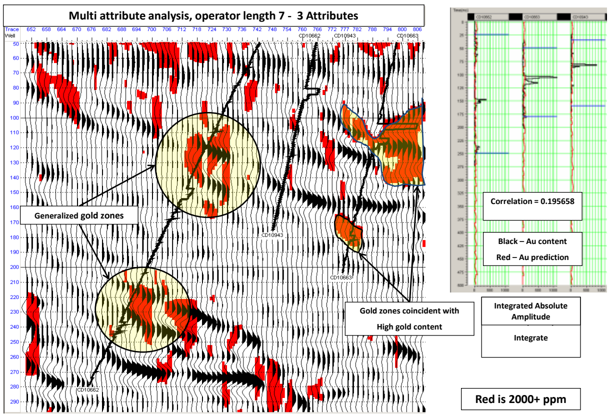

Figure 10. Multi-attribute analysis and association of anomalies to gold mineralised zones.

Moving to the region of sediment hosted deposits such as found in NT, we find that the data quality can vary from exceptionally good to poor. Again when the quality is high, a specialised analysis such seismic inversion can be utilised to associate anomalous impedance zones to mineralisation (Figure 11). At present, polymetalic skarn and IOCG type of deposits are considered as less favourable for seismic application.

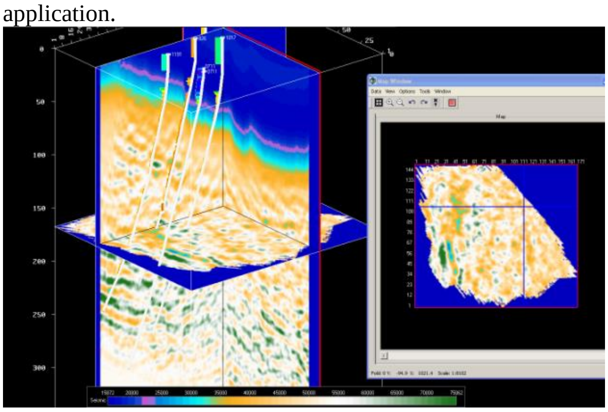

Figure 11. Impedance anomalies in 3D seismic may be related to ore zones.

CONCLUSIONS

Seismic is an incredibly powerful tool for mineral exploration. It can be used from regional to mine scale, for delineation of very deep structures to the detection of very small, complex bodies. It can be also utilised for mine planning and development. With a continuous development in the instrumentation sector we can expect that the cost of seismic surveys, particularly 3D, will go down and that seismic will become more frequently used, at all scales. This will enable further development and adaptation of the method. It will also improve our understanding of the variability and complexity of seismic images in hard rock environments, which is the key to further advancing this methodology and adapting if fully to suit exploration objectives of mineral industry.

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