Paper 35

Seismic Exploration of Ore Deposits in Western Australia

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ABSTRACT

Exploration for mineral deposits in a predominately hard rock environment is often quite difficult because of the structural complexities of the regolith and fresh rock. Potential field geophysical methods are typically used to detect major structures that may lead to the location of prospective targets. However these methods have low spatial resolution at depth and are limited to directly detecting shallow targets. The seismic reflection method is considered the most powerful geophysical method for detailed mapping of structures in petroleum exploration, but until recently has been considered to be of limited use in exceptionally complex hard rock environments such as the Yilgarn craton, Western Australia. To fully evaluate the feasibility of the seismic reflection method to explore for mineral deposits in this region, Curtin University's Department of Exploration Geophysics initiated an experimental program in 2004 that was supported by several major mineral exploration companies and the State Government research institute. Initial 2D seismic images clearly demonstrated that reflection seismic data is of great value to the mining industry. This research program has expanded over the last few years and evolved from basic 2D field trials at an experimental level to a stage where seismic methods have become a method of choice for precise targeting of extensions to existing deposits and mapping new mining targets. Novel seismic data processing and imaging techniques were successfully introduced into this program, and were a key element in encouraging industry to pursue further work. The improved image quality, combined with borehole log information has enabled expansion of the mining activities and the generation of several new exploration prospects. Thus, the stage is now finally set for the application of 3D seismic reflection methods. Additional support for 3D seismic has come from an analysis of off-plane events from crooked seismic surveys. A simplified cross-dip analysis and pseudo-3D pre-stack depth migration highlight the true 3D nature of the structures and establishes necessity for the application of full 3D seismic surveys. Planning for several large 3D seismic surveys to follow on the initial 2D studies are now underway. Here we present an overview of the developments and achievements, over the past four years, in the application of seismic reflection methods for mineral exploration in Western Australia.

INTRODUCTION

The greenstone belts of the Yilgarn craton, Western Australia, host numerous Archaean gold and base metal deposits. These deposits are typically found in complex geological structures associated with crustal scale shear zones. The prospective geology is commonly hidden by a deep, heterogeneous regolith cover consisting of weathered Archaean rocks as well as transported colluvial and alluvial deposits. Mineral exploration in Western Australia is in a mature phase and future discoveries of large deposits will depend on focused exploration programs where there is little or no exposure of Archaean geology. Successful exploration for gold and base metal deposits at greater depths and below areas of thick regolith cover is critically dependent upon an understanding of the location and geometry of the controlling structures at the scale of the deposits. This task is now rarely achieved by drilling alone and geophysical methods are routinely employed in exploration. Potential field methods, which utilise variations in rock physical properties such as, magnetic susceptibility and density, are used to interpret areas of prospective geology and structure. Electrical geophysical methods such as Induced Polarisation and Time Domain electromagnetic methods are used to directly locate (prospective) alteration and mineralisation. While these methods produce valuable information, the presence of thick conductive regolith makes the interpretation of complex, three dimensional structures ambiguous and uncertain. In addition, electrical methods suffer from a limited depth of investigation and limited vertical and horizontal resolution, particularly where highly conductive thick regolith cover is present.

The seismic reflection technique does not fundamentally lose resolution with depth; unlike magnetic, gravity, and electrical methods traditionally used for mining exploration. Consequently, seismic reflection surveys have the potential to provide images of underground structures at all depth levels. However seismic reflection methods have been rarely used in the hard-rock environment. A few studies (Salisbury et al., 2000; Milkereit et al., 2000) have documented the potential of seismic

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methods for all-out hard rock mineral exploration. Results from three-dimensional (3-D) seismic surveys over goldfields in South Africa (Pretorius et al., 2000) showed that under favourable circumstances, where there are large seismic impedance contrasts and flat, sub-horizontal rock units of a great extent, seismic methods can be effectively used to directly image deep gold-bearing structures.

Previous work in Western Australia across the Yilgarn craton has shown that deep reflection profiling can produce seismic reflections at depths greater than 2 km. Subsequently in 1999, several regional 2D seismic lines were recorded across several gold bearing structures in the Yilgarn. Again very clear images of deep structures were obtained but the seismic data failed to provide structural information at the mine scale Thus, while the data was good for developing conceptual targeting models in its delivered form it was of little use for exploration.

Two experimental high-resolution seismic lines were recorded over an existing gold mine in 2002 to test the ability of seismic methods to provide accurate images of relatively shallow structures (<1km deep), which are of direct interest to the current mining operations. Encouraging results were obtained, but further improvements in the seismic images were required to delineate extensions of gold bearing structures at depth. In 2002, we re-processed and re-analysed several low resolution (1999) and two high resolution (2002) seismic lines. The resultant high quality seismic images enabled the creation of a large research study, which was sponsored by four major gold companies. The Western Australian Government through Minerals and Energy Research Institute of Western Australia (MERIWA) provided substantial financial support for this study. Approximately 150 km of new high resolution seismic data were acquired for the project sponsors between February and April 2004. Initial results of this study are summarised in Urosevic et al (2005). Since that time seismic exploration in Yilgarn craton has accelerated, and the MERIWA project evolved into a larger research program (Centre of Excellence for High Definition Geophysics) sponsored by the state Government and supported by industry via targeted research grants.

The research program has diversified in the types of mineral deposits to be targeted (Gold, Nickel, Diamonds, Uranium, and Iron Ore) and is now focused on advancing in general the application of seismic methods for mineral exploration in a hard rock environment. One of the primary objectives is to maximise structural information from seismic data. To improve the seismic image quality specialised data processing methodologies have been designed and devised. A combination of data analysis utilising constant velocity panels, DMO, cross-dip panels and pre-stack depth imaging reveals that:

- 2D seismic line data provides accurate images under favourable conditions, which are met only in very few locations;
- Crooked seismic lines can be used to extract cross-dip information and may produce 3D images under favourable conditions (excessive line crookedness);
- 3D seismic methods are the only and ultimate (??) approach to delineation of complex structures at mine scale;

High quality seismic images, while essential, are not sufficient to guarantee the widespread use of seismic methods for mineral exploration. Another important component is the cost of seismic surveys, data processing and interpretation of the results. Manageable costs can be achieved by utilising:

- Small seismic crew (4-5 people) capable of operating a large number of seismic channels (300+)
- Using fully portable seismic equipment and sources
- Minimising the environmental impact (no line clearing)
- Optimising data processing efforts
- Interpreting results in several stages

Identification of lithological units is commonly achieved through seismic-to-log data correlation. Our research aims to establish statistical relationships between various seismic attributes (impedance, frequency characteristics) and elastic properties of different rock units in contact. Our goal is to achieve the ultimate aim in seismic exploration for mineral deposits: to identify the main stratigraphic units directly from the seismic data.

In this paper we show and discuss the results of our broad research efforts through several case histories.

Data analysis and processing issues

In the last four years we have processed and analysed numerous seismic reflection data acquired mainly across the Yilgarn craton (Figure 1). Last year we extended the analysis into a similar crystalline region of the Northern Territory. All of the regional seismic surveys were acquired by Geosciences Australia. Significant portions of recent experimental and mine scale seismic data have been acquired by Curtin University equipment, which now operates a 420 channel distributed (Seistronix) system.

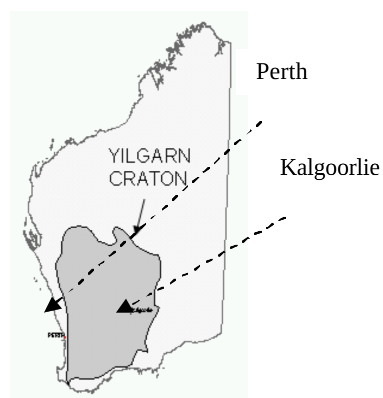

Figure1: The extent of Yilgarn Craton in Western Australia. Kalgoorlie is the mining centre of WA.

Over the last 10 years Geosciences Australia has acquired numerous regional seismic lines across Yilgarn craton. Most of the lines have crossed over existing mines. The wealth of information provided by these large scale regional seismic surveys was not initially recognised, or used for mineral exploration. The delivered seismic images provided a very clear representation of deep crystalline structures, but failed to provide structural information at the prospect or mine scale. Consequently, a view that reflection seismic cannot be used directly for targeting shallow structures and associated mineral deposits prevailed in the mining community for some time. Reprocessing of several regional seismic lines in 2002 revealed that the full complexity of the regolith (near surface altered, transported and weathered zone) had not been recognised and appreciated. This zone is typically very thick (up to 150 m), highly heterogeneous and apart from causing large variations in travel times can also scatter the seismic energy. Total static corrections (source plus receiver) can easily exceeds 200 ms in some areas. Thus if the travel time differences through the regolith section are not properly equalised, the shallow, high frequency reflections can be severely degraded or absent from the data. Such an example is shown Figure 2. The difference between the two images is only in the application of the refraction statics. Despite acquisition with wide geophone and source spacing, of 40 m and 80 m respectively, it is clear that the re-processed image can be used for mine scale exploration objectives. Reprocessed seismic data from a second regional seismic line that traversed another gold mine has been well verified against detailed geological knowledge and abundant drilling information (Figure 3). While these results inspired further reprocessing it also became clear that future acquisition parameters had to be modified to accommodate the complexities of structurally complex mining targets.

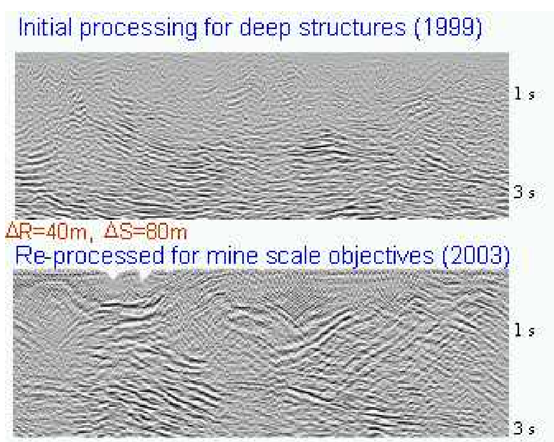

Figure 2: Initial (top) and Curtin re-processed 1999 seismic regional line (bottom).

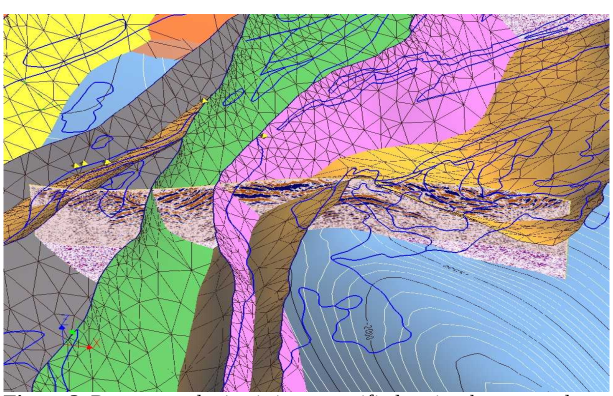

Figure 3: Reprocessed seismic image verified against known geology.

Subsequent high resolution seismic surveys further highlighted the effect of an heterogeneous regolith layer on image quality. Image quality becomes even more dependent on accurate travel time equalisation through the regolith zone. While accurate refraction static solution is a critical processing step it is not always sufficient for the generation of a high quality seismic image. Seismic data is often recorded either through the existing mine workings, or near it. The excessive levels of ambient noise affects the "first break" picking process. An example of high-ambient noise is shown in Figure 4. While high CMP fold is necessary in such a case, additional signal-to-noise (S/N) becomes necessary. (This is unclear to me) This is shown if Figure 5, where conventional multi-channel filtering (upper image) was not sufficient so that additional coherent noise suppression was necessary.

In addition to the ambient noise problem, the variable near surface conditions can further deteriorate data quality in dry conditions. In such cases poor coupling and increased scattering significantly degrade data quality.

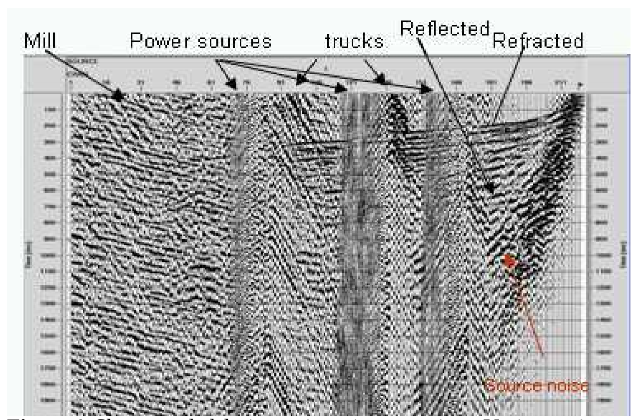

Figure 4: Shot recorded during active mine operations. Various noise sources are labelled.

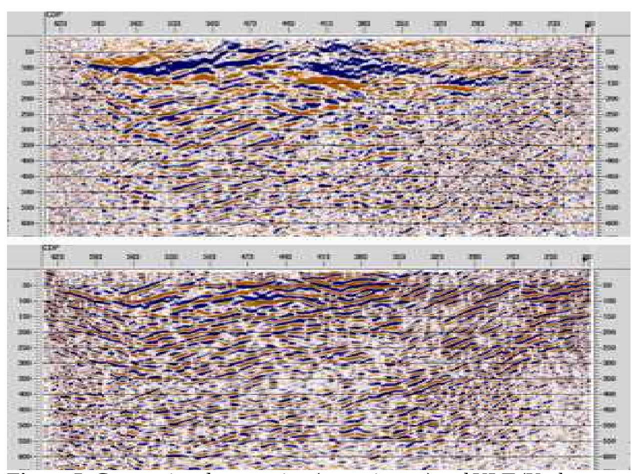

Figure 5: Conventional processing (upper image) and KLT (Karhunen-Loeve transform of the data covariance matrix) noise suppression (lower image).

Such an example is shown in Figure 6. Estimating the first breaks becomes extremely laborious, yet a reasonably good solution can be achieved. The rugosity of the regolith/fresh rock contact is often considerable, as can be seen in this example. Hence the precise travel time differences cannot be fully resolved with head waves (diving waves) and additional computations are required. This is commonly achieved through residual refraction statics.

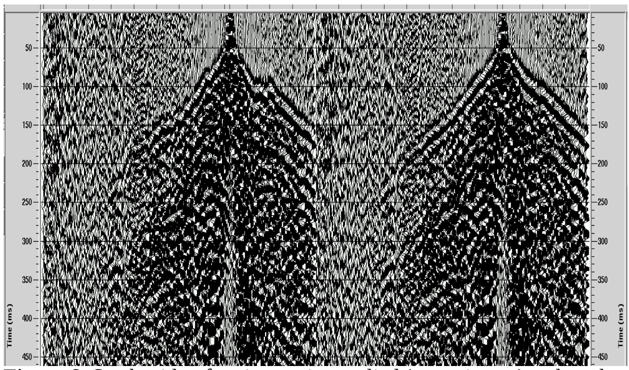

Figure 6: Stack with refraction statics applied (upper image) and stack with refraction and residual refraction statics applied (lower image).

The main problem with residual reflection static approach in a hard rock environment relates to the selection of a horizon(s) and a pilot trace. If a continuous event such as low order shear zone is not clearly visible in the data, the rest of the events (discontinuities and contact between various rock units) is often piece-wise and represented mainly by diffractions. Hence selecting a "horizon" to guide computation of surface-consistent residual reflection statics via some form of correlation cannot guarantee a good static solution across the entire line length. Instead our approach is as follows:

- Enhance first breaks (Burg deconvolution followed by a low pass filter)
- Apply LMO (linear moveout correction), select a short time window and train the system for neural net picking
- Pick end edit every shot record
- Compute and apply full refraction statics (regolith weathering) part + elevation part
- Select an offset range where only refractions of the fresh rock are present
- Apply LMO (fresh rock velocity smoothed over ½ spread length)
- Save the gathers and compute LMO stack
- Pick a pilot horizon (short smash, 7-13 traces)
- Compute surface consistent reflection statics on refractions

The advantages of this approach, which is a modified approach of Hatherly at al (1994), is twofold: a) selection of a "jumpy" pilot horizon is avoided; b) the first pass of velocity analysis is done on finally computed statics. An example of the above procedure is shown in Figure 7.

In some cases long wavelength static solutions may need to be solved. For this purpose refraction tomography may be used. However, such cases are rare, instead, refraction tomography is more useful to pick very shallow discontinuities, which are mostly relevant to open cut mining. Refraction tomography can also be valuable for underground mining when interpreted together with reflection seismic images. An example is presented in Figure 8, where abrupt changes in the velocity field closely match near surface faults depicted from borehole information. An additional use of the refraction tomography could be for pre-stack imaging.

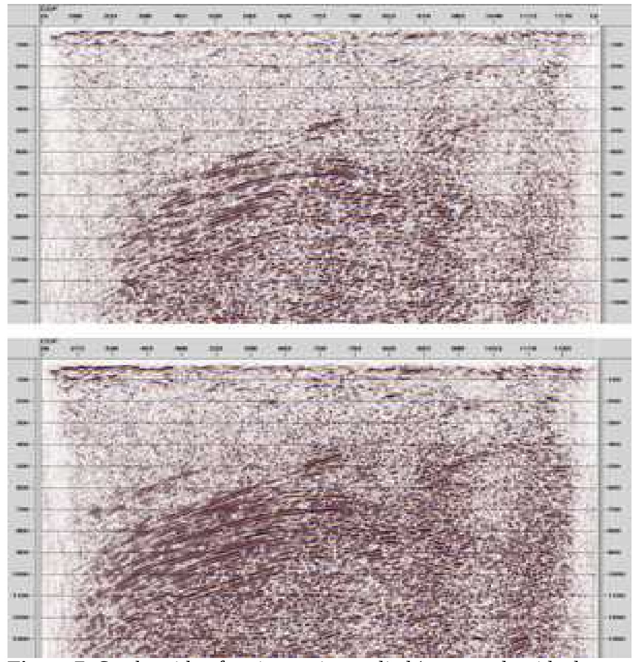

Figure 7: Stacks with refraction statics applied (upper and residual refraction statics applied (lower).

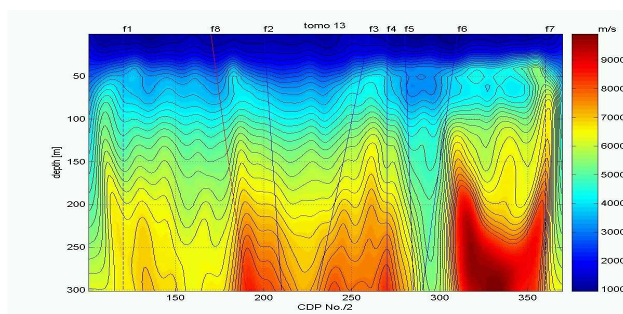

Figure 8: Refraction tomography used to delineate near surface (regolith) discontinuities. Faults overlayed are from drilling information.

Seismic imaging in hard rock environments

Once the regolith cover is "homogenised" by static corrections, further data processing, in our view, becomes inseparable from structural interpretation. From extensive drilling, logging and core sample measurements we know that the real velocities in hard-rock are in the range 4.5-6.5 km/s. Our best stacking velocities are, however, dip dependent, while complex diffraction pattern make velocity estimatation a daunting task. The first velocity analysis pass is carried out by using "old fashioned" constant velocity stacks (CVS). The full line extent is used for such analysis for several reasons:

- Better chance to "postulate" the most likely structural play,
- Off-the-plane events can be recognised, or at least suspected,
- Resultant velocity errors (caused by limitations in "visual" estimation of which event is the most coherent and with the strongest amplitude) will typically have negligible effect on the stack quality and also further processing steps,
- Structural interpretation begins at this stage.

This leads to several basic CVS analysis "rules":

- Steeply dipping events appearing with low stacking velocities originate from off-the-plane structures (typically from shallow structures or discontinuities within the regolith),
- Steeply dipping events expressed on very fast velocities (higher than 7.5 km/s) may be difficult to fully preserve in the final stack and CVS should be preserved for the final interpretation,
- Events expressed over very small velocity range are commonly originating from the deeper structures which are unfavourably oriented with respect to the line direction.

In Figure 9, off-plane events originating from shallow structures are apparent in the CVS top panel while "real" steeply dipping events appear on very fast stacking velocities.

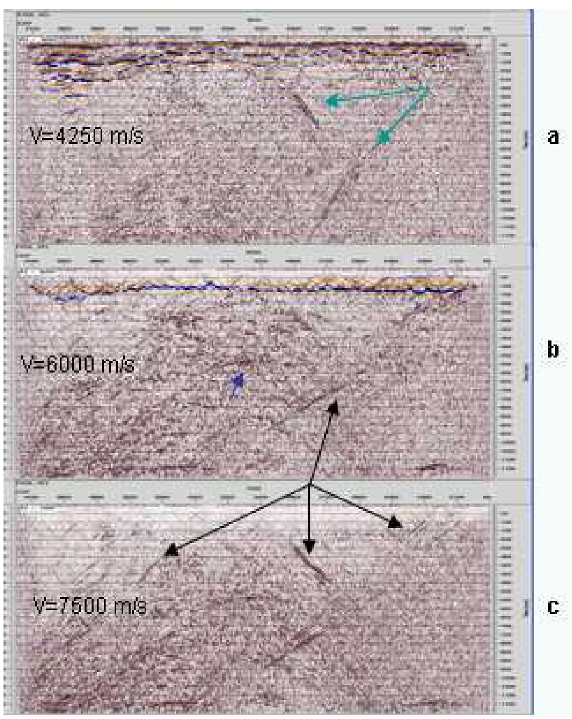

Figure 9: CVS panels: a) V=4250 m/s, b) V=6000 m/s and c) V=7500 m/s. Off-the-plane events are denoted with green arrows, blue arrow indicate sub-horizontal events appearing at geologically expected velocities and black arrows mark steeply dipping "real" events.

A priori geological knowledge (or expectation), gravimetric and/or magnetic maps over the area, and log information are very helpful for CVS analysis. The seismic processor needs to know what coherent features can be trusted before a velocity model is built.

The fact that real events (events originating in the plane of the line direction) come with dip dependent velocities and that numerous diffractions cross-over each other with conflicting dips, poses the necessity for some form of pre-stack imaging. The method of choice is certainly full pre-stack depth migration. However this method is not easy to implement in hard rock environments due to notoriously low S/N ratio and needs to be proceeded by partial pre-stack migration such as DMO (dip dependent move-out correction). In general DMO reduces the reflection point dispersal and enables conflicting dips to be stacked with similar velocities. Consequently post-DMO velocity analysis brings stacking velocities closer to the real geological velocities and enables preservation of steeply dipping events (Figures 10a and 10b). This process also enables much improved performance of post-stack migration techniques (Figure 10c).

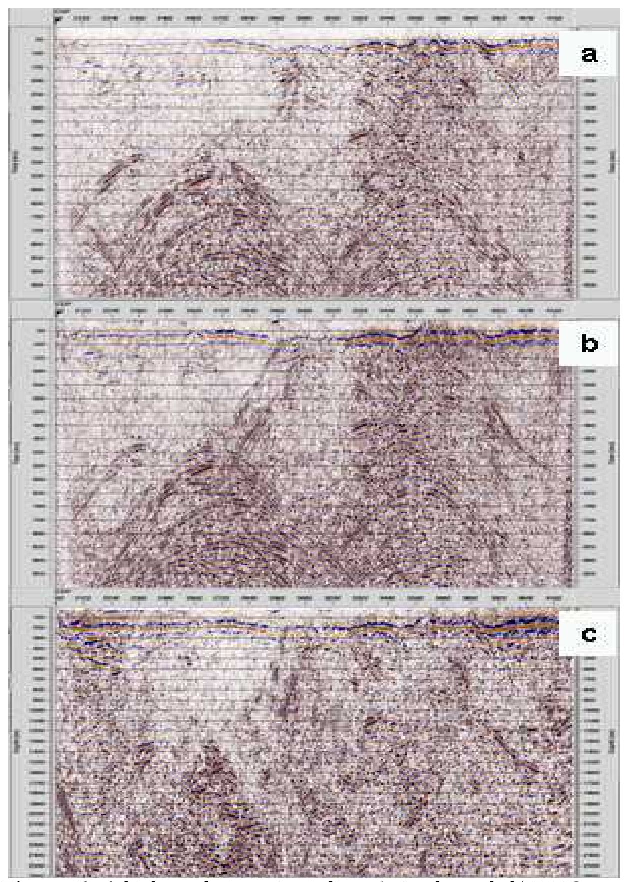

Figure 10: A high-resolution seismic line: a) simple stack, b) DMO-stack and c) migrated DMO stack. Note enhanced steeply dipping events after application of DMO corrections.

Conventional DMO is better suited for a continuous, layered structure rather than piece-wise geological bodies. An improved approach to the same reflection smearing issue termed multifocussing (Berkovitch et al, 1994) which considers a reflection segment (reflection curvature) rather than a point can further enhance steeply dipping events (Figure 11). While this process outperforms conventional DMO, it is expensive and has other issues related to the points of event cross-over. In principle, one would prefer having both solutions at hand.

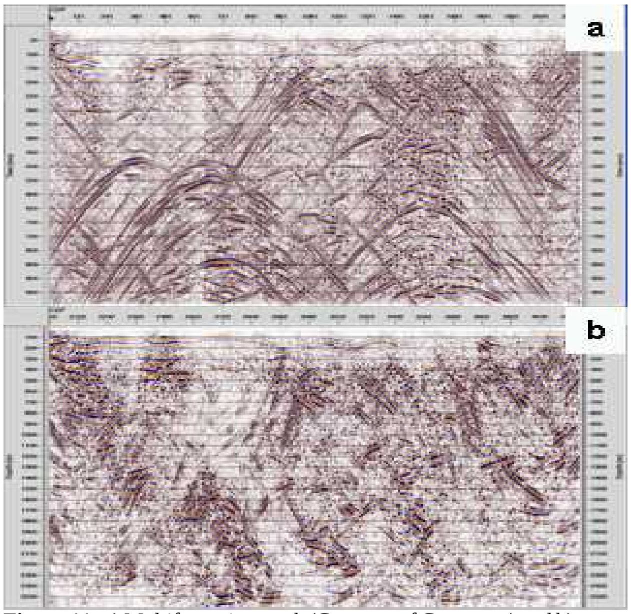

Figure 11: a) Multifocussing stack (Courtesy of Geomage.) and b) migrated multifocussing stack. Compare these two images to the equivalent DMO and DMO migrated stacks of Figure 10.

Clearly either a DMO or a multifocussing stack should always outperform a simple stack. However, in a hard rock environment this is not always the case, particularly when 2D seismic (straight line or crooked) is considered. In some cases a DMO stack produces an inferior image in comparison to a simple stack, or the two appear quite dissimilar. This occurs when the line orientation (or the segment of the line) is not in the dip direction and the recorded events are projected into the plane directly underneath the seismic traverse. Such a situation is common to many interfaces due to the complex geology of most mineral deposits.

Providing that optimum conditions are met for a 2D seismic survey (dip direction and 2.5D geology), the best imaging technique is certainly pre-stack depth migration (PSDM). The performance of this method is greatly dependent on the accuracy of the input velocity field. Hence iterative velocity building via image gather analysis is a natural component of the PSDM process. However velocity building also requires a reasonably good pre-stack S/N ratio. This condition is rarely or never met by hard rock seismic data. In addition, 2.5D structures are virtually non-existent in hard rock environments. To work around these issues we commonly use PSDM in the following way:

- Apply post-stack migration of DMO stack (if time migrated then convert to depth, or use depth migration)
- Gather log data, geological model, etc.
- Use post-stack depth image to construct velocity field for PSDM
- Compare PSDM output to post-stack image and expected geology, refine the model and repeat the run.

This process is illustrated in Figure 12. Clearly PSDM has great potential in hard rock imaging, and its true power is yet to be properly evaluated for hard rock seismic exploration.

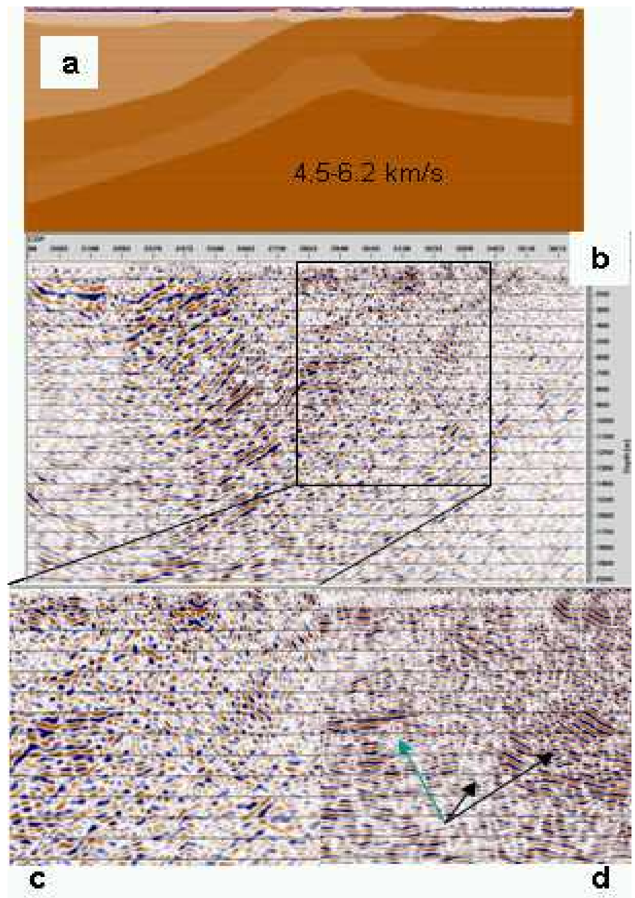

Figure 12: a) Velocity model in depth, b) Depth migrated DMO stack, c) enlarged part of image in B) and d) equivalent PSDM image (Kirchhoff integral method). Clearly the imaging results can be distinctly different and a priori knowledge of geology is helpful in estimating an optimum output.

Crooked seismic line processing

In most cases, seismic reflection data acquisition is restricted to existing roads and bush tracks. Consequently, crooked line surveys are common in a hard rock environment. This further violates the common (and implicit) assumption of seismic line direction coinciding with the dip direction of the underground structures.

Standard crooked line data processing produces in most cases clearer images, offering a wealth of structural information to an interpreter. Yet careful analysis shows that underground reflection points are often produced by geological features which are far away from a selected mid-point track. Early identification of these out-of-the-plane reflections can be achieved, to some extent, by:

- analysing constant velocity stacks;
- by comparing the quality of pre- to post-DMO stack;
- by analysing the performance of post-stack time and depth migrations.

However, more explicit assessment can be achieved through a simplified cross-dip analysis. Such analysis also offers a procedure for constructing a 3D velocity model that can be subsequently employed for 3D pre-stack depth imaging. The effectiveness of this approach is dependent upon crooked line geometry and the data fold. In general, highly deviated lines bring the crooked line imaging task closer to that of true 3D survey.

This problem has been rigorously treated and analysed by Nedimovic and West (2003). They show that a combination of 3D geology and crooked line seismic data acquisition can be used to analyse cross-dip effects, partially compensate for them, and obtain improved seismic images. Our approach is to use cross-dip analysis for structural interpretation and for building a 3D velocity model (Urosevic and Juhlin, 2007). As crooked line surveys are in effect 2.5 D surveys, or swath surveys, it is possible to at least partially build up a 3D model based on the cross-dip analysis. Hence it makes more sense to apply 3D rather than 2D imaging routines in these cases. Still inherent to 2.5 D surveys is the lack of illumination in the cross-dip direction, and uneven fold and offset-azimuth distribution in the bins. Another significant issue is the reduction of fold from the selected central CMP track which is a particular concern for hard rock seismic due to the typically low S/N ratio.

Where there is a significant spread in the midpoints perpendicular to the profile (selected mid-point track) it is possible to analyse the seismic data for the cross-dip component of the reflections (Nedimovic and West, 2003). If the reflector dips exactly perpendicular to the strike of the profile then the cross-dip component can be corrected by

$$\Delta T = (2 \cdot \Delta Y / v) \cdot \sin\phi$$

where ΔY is the signed perpendicular distance from the midpoint to the CDP stacking line, v is an appropriate constant velocity estimate of the medium, ϕ is the cross-dip angle and ΔT is the time delay or advance to be applied to the trace in the CDP gather. By stacking data with different cross-dip corrections for a given stacking, or NMO velocity, an estimate of the cross-dip component can be made. If the strike of the reflector is not parallel to the CDP stacking line then the cross-dip correction also depends upon the dip. Therefore, the cross-dip angle obtained should be considered with caution, but is reasonably accurate for gently dipping reflections at all strikes. This simplified correction enables quick and efficient analysis of the off-plane events and eventually can be used to assist in building a 3D velocity model for pre-stack migration.

The selected example comes from a typical hard rock environment, deep in the Northern Territory desert. In this case a regional seismic line of moderate to low resolution was acquired to investigate deep crystalline structures. Parts of the seismic line which traversed several gold mining prospects were subsequently reprocessed. A vast improvement of the image quality in comparison to the initial processing was mainly attributed to accurate computation of refraction and residual static corrections. Despite the crooked nature of the line, coherent images were obtained with a conventional processing flow which involved DMO and post-stack migration (Figure 12). Analysis of CVS panels suggested that some events may be off-plane. It is also apparent from Figure 13 that shallow events migrate better than deeper events. Subsequently we selected one of the line segments for cross-dip analysis and imaging tests. Cross-dip analysis confirmed that line direction was favourable for shallow structures but less so for deep structures (Figure 14). To further resolve this issue we re-binned the data into a 3D grid, constructed pseudo 3D velocity model and performed 3D pre-stack depth migration (Figure 15). The resulting images suggest that some events originate far away from the selected mid-point track. Despite encouraging results it is clear that only a true 3D seismic survey could fully resolve these complex, three-dimensional structures.

A true, all-azimuth 3D survey is relatively expensive, and is typically recorded only over well-explored and highly prospective areas (such as an existing mine site) where there is clearly identified value in the survey data. Furthermore, in such environments, field data acquisition is faced with various obstacles: a) mine infrastructure, b) high ambient noise, c) restrictions on the type of source that can be implemented, d) environmental issues (ground clearing permission nearly impossible to obtain now in Australia). Consequently the time period from the planning and 3D design to execution can be quite lengthy.

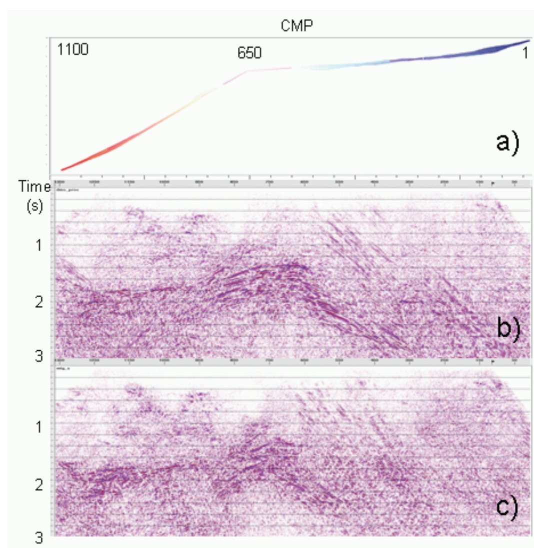

Figure 13: a) Seismic line track recorded over prospective gold deposits, b) DMO stack and c) post stack time migration. Note that shallow steeply dipping events migrate in expected positions. Deeper reflections are stronger and more coherent in b) than in c).

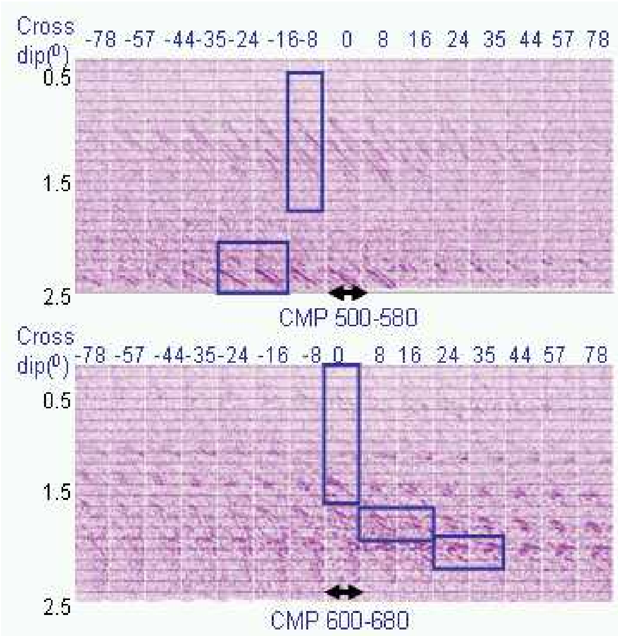

Figure 14: Crossdip analysis. Shallow reflections display small crossline dip angle. Dipper structural shapes appear more complex (lower panel, CMP range 600-680).

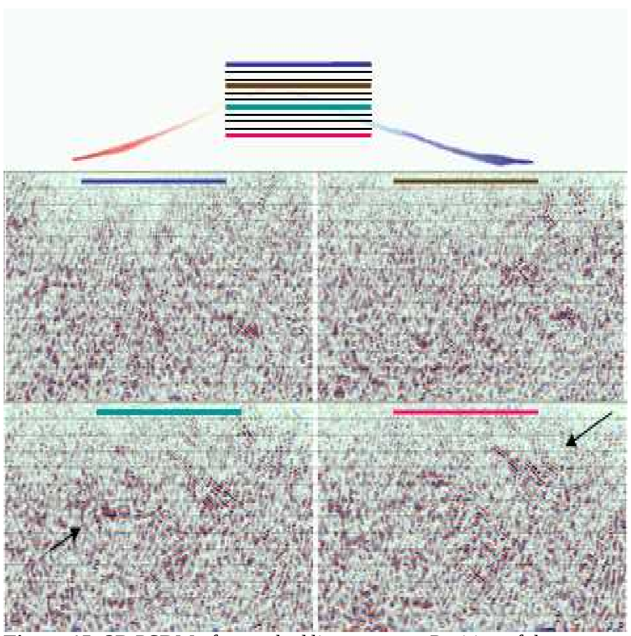

Figure 15: 3D PSDM of a crooked line segment. Position of the output in-line and the corresponding image are colour connected. Note that last two images (green and blue) which are far away from the central track show most coherent images.

3D experimental survey

A test, mini-3D survey example is briefly discussed here to highlight some issues that can trouble 3D seismic in hard rock environments, but also shows the potential value of this approach for exploration. The survey was been designed around a very small area to test if 3D seismic could provide useful information regarding highly variable iron ore grade within an alluvial channel, situated in a hard rock setting. Dense scrub/bush and environmental restrictions (no clearing, no foot-print) required the use of a very light, portable source (45 Kg accelerated, DC driven weight drop). The total number of available channels was 286. The time frame for the survey was 7 days which included a 2 km long 2D seismic line and a mini 3D area (Figure 16a). Geophone and shot spacing was 5 and 10 m respectively. Dense vegetation, heterogeneous and dry near surface, and strong wind accompanied this survey. The application of a low-power source and low CMP fold did not help the data quality. Still the channel structure was imaged well, even by the 2D line. A basic 3D processing flow and subsequent time slice analysis revealed that intra channel heterogeneities, which may relate to the variation in ore grade, are likely to be well imaged by the 3D seismic method (Figure 16c). The final conclusion awaits drilling results.

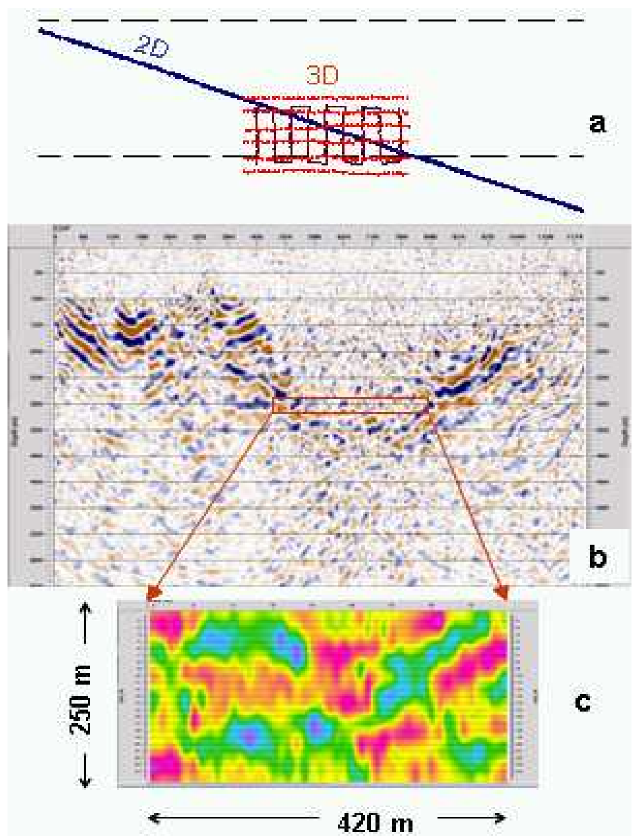

Figure 16: Experimental seismic survey: a) 2D and 3D surface layout. Receiver lines shown in blue, shot lines in red. b) 2D migrated stack and c) Time slice from 3D mini data cube.

Interpretation of seismic images

The structural complexity in a hard rock environment means that seismic interpretation is inseparable from data processing, and is it also dependent on the geometries and parameters used for data acquisition. Interpretation starts at the stage of velocity analysis (constant velocity panels). Very often with 2D seismic surveys (straight or crooked) several slightly different velocity models produce a stacked section with equally plausible structural plays. Hence, geological input or log data are essential at this stage for the selection of the initial velocity field and for further processing. Subsequent stages of interpretations involve: a) structural interpretation on the cosine of the filtered trace envelope, b) refinement on the amplitude section, c) well-tie and correlation and d) identification of various lithological units. When new borehole information becomes available, interpretation is further refined, just as geological interpretations are refined when new drill data becomes available.

At present, mining operations in Western Australia are moving underground following the structures of earlier diggings, as this is more cost effective than finding new deposits. Hence extrapolation of ore body horizons in depth via seismic imaging is one of the essential tasks. At present, deep boreholes are sparse in Australia, and rarely logged with sonic tools. In such cases, in order to establish necessary correlation between seismic events and various rock units in contact we have adopted the strategy of "reviving" the old un-logged boreholes. For that purpose we select three core samples per lithological unit (usually readily available) and measure (average) velocities and densities. From this data an impedance log and/or pseudo-synthetic seismogram is constructed and used to establish a seismic-well tie (Figure 17). It is clear that tracing the extension of the mining target away from the borehole, in this case a gold bearing rock unit, is straightforward. In the case when line orientation is favourable with respect to the underground structures and the geology of the area is well understood, prospective ore bodies are targeted directly from seismic data. An example from St Ives gold mine is shown in Figure 18.

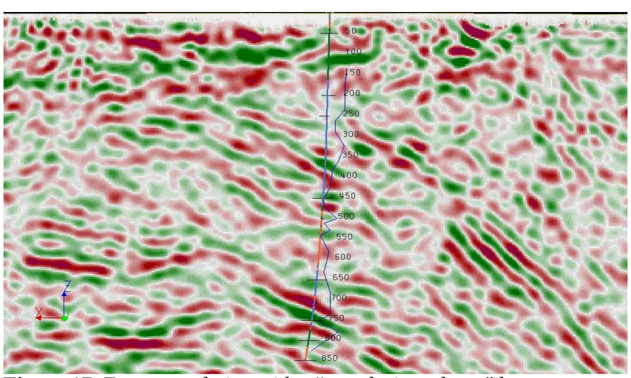

Figure 17: Event correlation with a "pseudo-impedance" log.

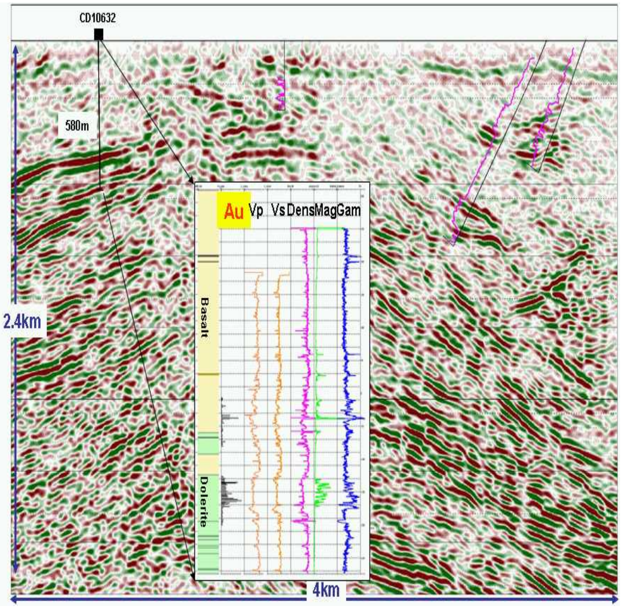

Figure 18: Direct targeting of gold bearing structures from seismic data. Two boreholes (pink impedance logs) struck gold bearing ore bodies at 600 m and 1000 m, respectively within 10m of predicted depth.

An additional interpretive use of seismic data, in particular for gold and nickel exploration, is to refine the global structural model and provide improved constraints for inversion of potential field data (Figure 19).

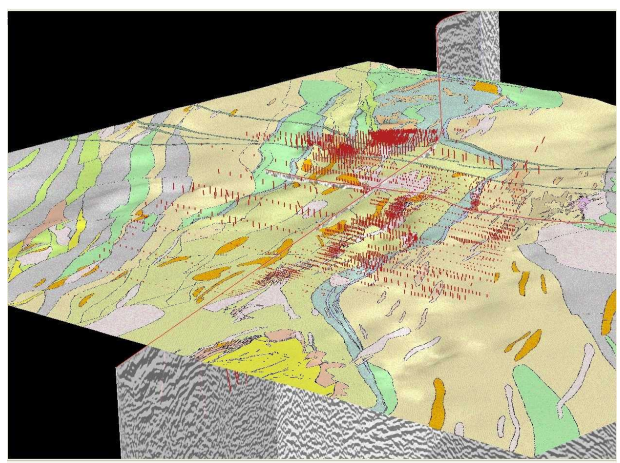

Figure 19: Integration of geophysical methods, St Ives mine camp.

The final and ultimate use of seismic data in mineral exploration is direct identification of rock units through seismic inversion (Figure 20). Full Waveform Sonic logging can be used to build a statistically significant relationship between seismic attributes, such as acoustic impedance, for rock units which are of interest to mineral exploration. This is particularly important for gold exploration where direct geophysical signatures are absent.

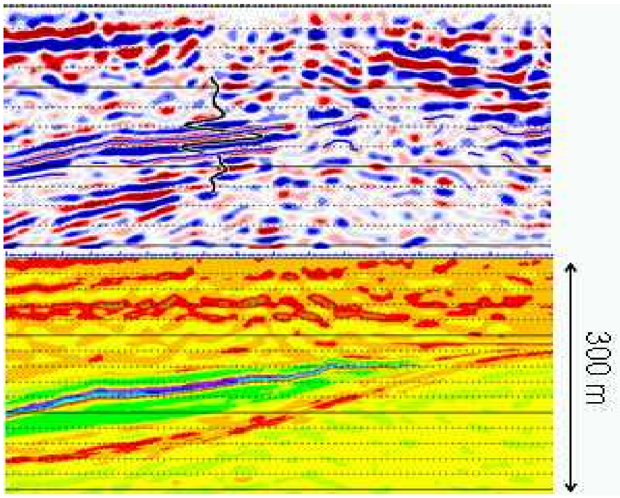

Figure 20:. Model-based impedance inversion used for targeting gold bearing dolerites.

CONCLUSIONS

Based on seismic images, the orientation and the dip of several major and minor shear zones have been successfully determined, and in some cases previous geological models were modified or completely changed. Extensions of gold bearing structures at greater depths have been delineated in several cases and new drilling targets were identified. Direct targeting of new ore bodies from seismic data have been successful in several cases. Our understanding of the seismic signature of hard rocks has greatly improved over the last few years. As the data from 2D surveys are less than perfect necessity has provided the impetus to create various means to extract more information from these surveys. Several advances have been made in data processing and imaging techniques. In addition, the role of interpretation in guiding the processing and imaging is becoming more science and less art. The first seismic inversion trials appear promising and open new avenues for interpreting seismic data in hard rock environments. However, there is lot to be learned and accomplished in an often overwhelmingly complex geological setting. Wider use of 3D seismic methods and better use of boreholes should be crucial for further advances in seismic exploration for mineral deposits.

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