Towards direct detection of gold bearing rock formations from seismic data: St. Ives gold camp, Western Australia

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Summary

The utilization of seismic methods for mineral exploration, particularly in Western Australia has become widespread in the last few years. In the initial stage the use of seismic data was limited to the structural interpretation only. Subsequent lithological interpretation however required introduction and testing of new techniques and methodologies, such as inversion and attributes analysis. While these techniques are considered mature by hydrocarbon standards, their application in hard-rock environments still requires extensive study to determine the veracity of the results.

Challenges to hard-rock seismic methods begin at the acquisition phase where factors such as remoteness and inaccessibility of the site and environmental restrictions, result in seismic lines being misaligned with the dip of the dominant structures. Further, massive shear zones, faulting, folding, and dyke intrusions, common for these areas, result in extremely complex subsurface structures which also compound seismic images. The regolith, a near surface zone up to 150 meters thick comprised of altered, transported, and weathered material causes energy dissipation and time delays in seismic mapping of hard rock environments. The lack of borehole data with sonic logs also contributes to the difficulty of seismic data calibration and hence full utilization and analysis of seismic information.

Preservation of amplitude, frequency content and phase of original signal is a prerequisite for inversion and attribute analysis. However, the complex structure, seen in mineral exploration in Western Australia, makes this task cumbersome. Inherently low signal to noise ratio and variable receiver and source ground coupling, presents a problem for true amplitude processing of hard rock seismic data. We show that each of the challenges facing hard-rock seismic has a systematic solution. This leads towards the final aim which is to accomplish the lithological interpretation by directly relating seismic impedance and attributes to the various rock formations in contact.

Introduction

In 2004, GoldField and Curtin University of Technology undertook a project to asses the feasibility of the application of high resolution reflection seismic for gold exploration in Western Australia. A large scale regional survey several years before had indicated that deeper structures can be successfully imaged with course seismic acquisition techniques. These surveys provided images only on a regional and camp-scale while shallower structures of direct interest to exploration remained unresolved. It turned out that the acquisition of high resolution seismic aimed to detect economically viable targets for mineral exploration is not a trivial endeavor. Seismic lines which wander through busy mine site roads, around restricted areas, and through untenable terrain result in a crooked-line geometry, often saturated with ambient noise, and running in an unfavorable direction with respect to the dominant trend of the major structures. The presence of out-of-plane reflections is hence commonplace. This limits the effectiveness of pre and post stack imaging techniques and severely affects the calibration with sonic logs. While mine-sites are no stranger to borehole drilling, sonic logs, where available, are generally sparse and often restricted to shallow depths by hydrocarbon standards (200-900 meters) which presents further problem for seismic data inversion and subsequent lithological interpretation.

Area of investigation

This study focuses on the East Victory seismic line at the St. Ives gold camp in Western Australia (Figure 1). The St. Ives gold camp is located on the Yilgarn craton, an archaean mafic sequence made up of basalts, ultra-mafics and interflow sediments. These formations are found primarily in a southerly plunging anticline, overlain with unknown crusts of felsic composition and intruded by dolerites and felsic porphyries (Drummond et al, 2000). The line is crooked, but not to an extent to enable specialized crooked seismic line processing as suggested by Nedimovic and West (2003) and Urosevic and Juhlin (2007). As illustrated in Figure 1, the line was orientated approximately in the dip direction of the dominant anticline in the area.

Towards seismic detection of gold bearing formations

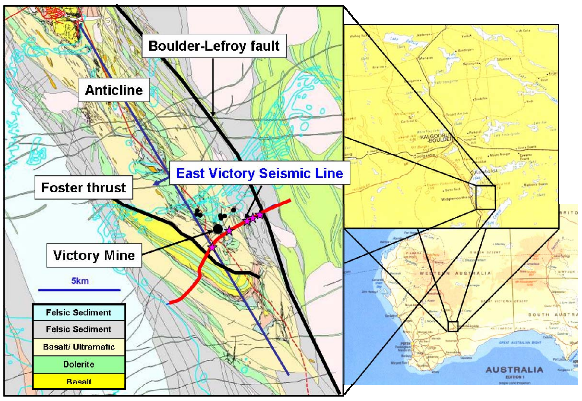

Figure 1. The East Victory seismic line located at the St. Ives gold camp, Western Australia.

Seismic data processing

Inversion and attribute analysis require minimal distortion in original reflection amplitude, frequency, and phase. Control of these factors ensures less ambiguous results when calibrating borehole sonic log information to the seismic image data. The complex structures, highly heterogeneous regolith zone, high ambient noise and variable source-receiver couplings, however, present serious challenges to preservation of relative amplitudes. For 2D lines oriented in the dip direction of the dominant structures, pre and post stack migration techniques are essential for generation of interpretable structural images. One of the key requirements is accurate velocity analysis which, in hard rock environments, could only be achieved by the application of the old-fashioned constant velocity stack analysis in combination with dip moveout corrections and or common reflection surface (CSR) approach.

The processing flow is detailed in Figure 2. The red boxes indicate where multiple iterations were required for velocity model creation. The band-pass filters were designed to retain the original reflection frequencies of approximately 30-90 Hz. Random and ambient noise was attenuated during stacking and by post stack application of F-X deconvolution. The resulting seismic image is displayed in Figure 3. The inset image presents the map view of the seismic line with labeled camp-scale features. Reflections on this image were confirmed through projections of several camp-scale features including, the Foster Thrust, the Repulse fault, and the Condensor dolerite. The St. Ives anticline structure is seen quite clearly on this image. The resultant images were zero phased prior to inversion and attribute analysis.

Geometry Assignment
First break picking
Elevation statics
True Amplitude Recovery
Spiking Decon
Refraction analysis and correction
Trace envelope gain
Bandpass Filter (Butterworth – 20-30-140-
Automatic Gain Control
Residual statics analysis and correction
Bandpass Filter (Butterworth – 20-30-90-30)
Velocity Stack Analysis + NMO (forward)
Ensemble DMO in T-X domain
NMO (Inverse) + Velocity Anal. + NMO (forward)
Bandpass Filter (Butterworth – 20-30-90-30)
Stack
F-X Decon – F-X Decon – F-X Decon
Steep Dip Explicit FD Time Mig
Time to Depth Conversion

Figure 2. Processing flow for the East Victory line.

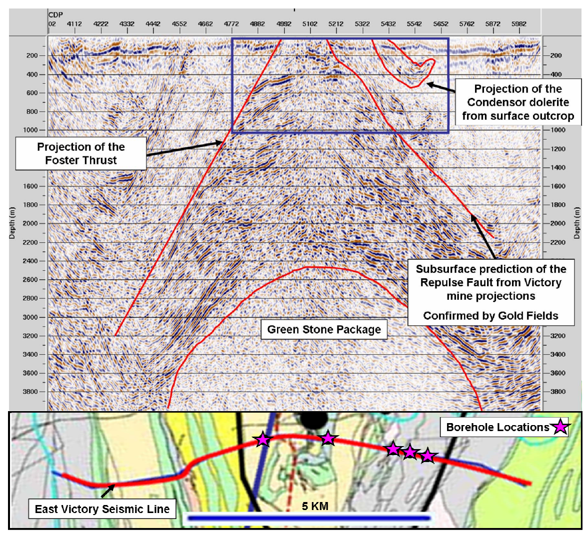

Figure 3. The post stack migrated East Victory seismic line. Several camp scale features confirmed the accuracy of this including the Foster Thrust, the Condensor dolerite, and the mine projection of the Repulse fault. The inset image shows the map view of the seismic line and camp scale features. The blue box indicates the focus area for this study.

The accuracy of seismic inversion and attribute analysis is particularly important for the shallow structures that are of immediate exploration interest (0-500 m).

Seismic to well tie

Calibration of seismic images with borehole sonic logs is necessary for the inversion process. The correlated synthetic seismograms form a statistical basis for identification of lithology, structural features, alterations and potentially prediction of gold bearing formations away from the borehole. A good quality full-waveform sonic (FWS) data are necessary for this process. This is however rarely the case in hard rock environment. Consequently the inversion process is poorly constrained and requires addition of on-site geological information.

Five boreholes with sonic logs were available on the East Victory seismic line for calibration of seismic data, seismic inversion, and attribute analysis (Figure 3). Rock characterization was carried out on all boreholes by methods suggested by Gardner et al. (1974), and Castagna et al. (1985). These methods are known, in hydrocarbon exploration, to characterize rocks based on porosity, fluid content and lithology. Analogous responses in hard-rock environments would be mineralization, shear zones, and lithology. Extant rocks were further cross-plotted based on rock type, structure type, and alteration type.

Results from the boreholes on the East Victory line indicated that rock characterization was statistically viable regarding the rock and structure type. Salisbury and Snyder (2004) has shown that alteration type also effects rock characterization, but available data was too weak in this case to warrant further study. With only 5 sets of boreholes and sonic logs available for study, error-analysis was limited.

Amplitude versus offset

Amplitude versus offset (AVO) studies are an untested technology in mineral exploration in Western Australia. AVO results are highly dependant on changes in velocity, density and Poisson ratio (Sheriff, 2004). Rock characterization within the East Victory rock data has indicated that a very small gradient change occurs for various rock types in contact.

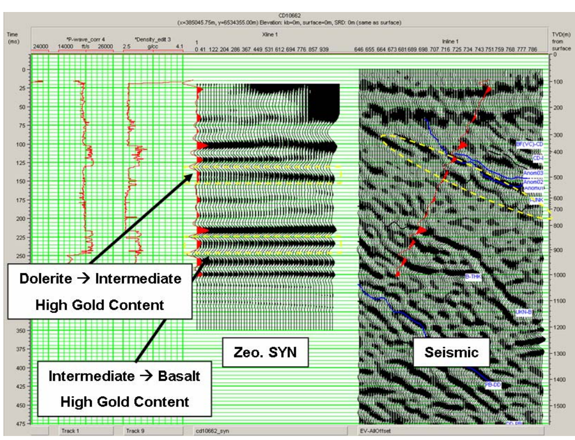

Figure 4. Amplitude versus offset calculations for borehole CD10662. High gold content zones are indicated.

Some AVO effects were observed in the offset range from zero to 1000 meters for borehole CD10662 (Figure 4). The calculations indicated weak amplitude versus angle variations. Reflection coefficients tended to be low, under 0.08, with no polarity changes. High content gold zone, as indicated in Figure 4, show an AVO trend of increasing amplitude with offset.

Seismic inversion

Linking lithological contacts through empirically derived trends to acoustic impedance from boreholes is the goal of inversion studies in hard rock environments. Inversion data however suffers from non-uniqueness enhanced by the processing errors, low signal-to-noise ratio, lack of check-shots, wavelet distortions, sonic logging errors, and in general relatively low sonic-to-seismic correlation.

Analysis of the synthetic seismograms and AVO effects using all borehole data however indicates some correlations between reflection amplitudes and rock types, alteration zones and structural features. Borehole control was highest on the eastern section of the study area (Figure 5). Without check-shots, correlations between the synthetic seismogram and the seismic data required multiple iterations of log-stretching and time-and-phase shifting to achieve an average 0.723 cross-correlation coefficient which is taken as satisfactory for further analysis.

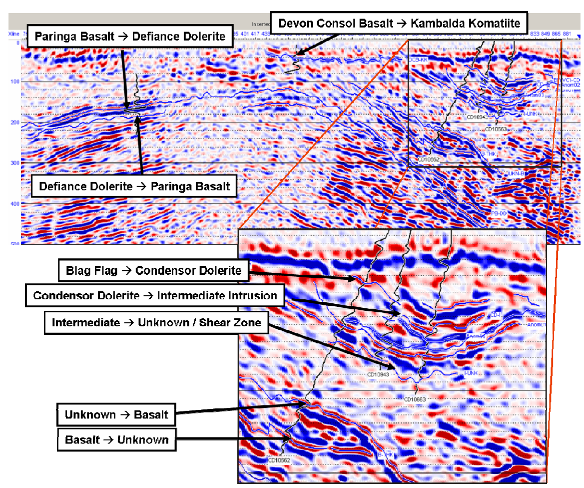

Figure 5. Synthetic seismograms correlated with seismic data. Main contacts have been traced and labeled.

Various inversion approaches were tested. Error analysis of the inversion has been assessed by using the approach of the "hidden" boreholes. The two top performing inversion schemes were the model based and band-limited approaches (Figure 6). Each inversion showed approximately the minimum prediction error for the Condensor dolerite, and several intermediate rock contacts. High gold content structures were observed throughout the intermediate rock contacts.

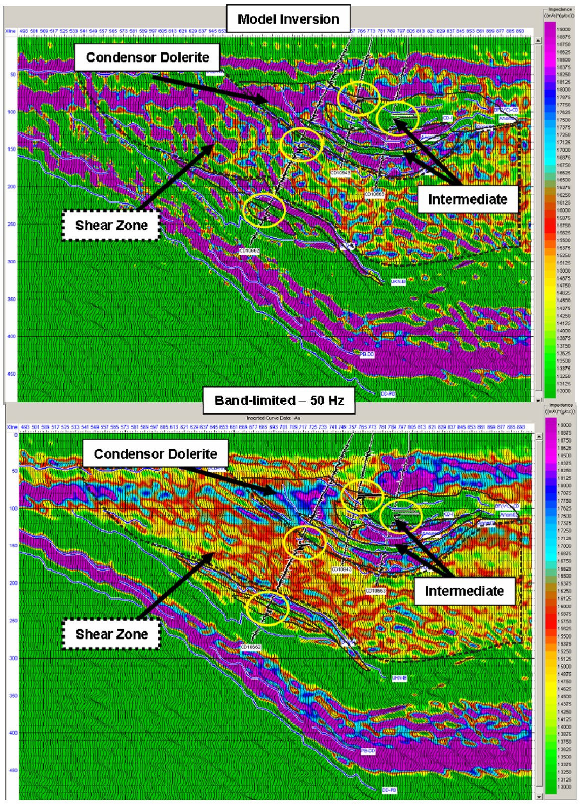

Figure 6. Model-based (top) and band-limited inversion (bottom) of the East Victory Seismic line.

Attribute Analysis

The study of attribute analyses was performed in an attempt to predict the distribution of various rock types. While inversion utilizes known acoustic impedance with matched rock contacts for predictions throughout the seismic section, attribute analysis uses suspected ties between rock properties from the log and wave field attributes for predictions throughout the seismic section.

Hydrocarbon exploration tends to use attribute analysis for porosity predictions in regards to reservoir properties. Mineralization at alteration plumes and at structure changes is an analogous form to porosity in hard-rock environments. The only quantifiable log-property that corresponds to mineralization or an altered rock is Au content. Geostatistical analysis showed that three attributes: narrow filter range 25/30-35/40, dominant frequency and instantaneous phase have the highest correlation of 0.195658 with Au content. These results were consistent through the East Victory seismic line (Figure 7). Using borehole gold contacts as reference, predictions show high gold content rock associated with extensions of three intermediate rock contacts and a shear dolerite.

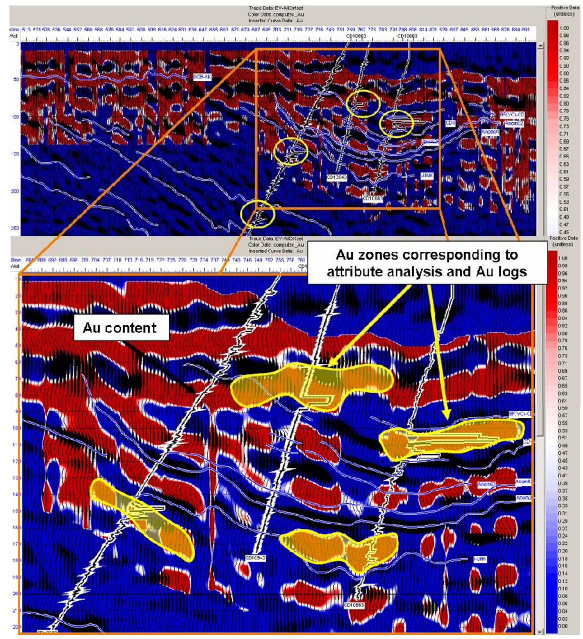

Figure 7. Gold content predictions through attribute analysis on the East Victory seismic line.

Conclusion

Processing, inversion and attribute analysis has been conducted on the East Victory seismic line at the St. Ives gold camp in Western Australia. Processing results were confirmed using both surface geological interpretations and borehole log control. Inversion for rock-type prediction, while still ambiguous, have a higher probability of success with an increased borehole control. Attribute analysis predictions show promise for direct prediction of gold bearing formations, but require further verification.

Acknowledgement

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