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Processing and seismic inversion of the Intrepid seismic line at the St. Ives gold camp, Western Australia

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ABSTRACT

The use of seismic methods in mineral exploration has considerably increased in recent years in Western Australia. However, unlike in sedimentary environments, seismic exploration in hard-rock environments is cumbersome. Difficulties commence with data acquisition in relation to mine-site locations, restrictions, and inaccessibility resulting from seismic lines being not aligned with dominant structures. The regolith, which consists of altered, transported, and weathered material up to 150 meters thick, scatters seismic energy and produces variable time delays (static corrections) that could exceed 200 ms in some areas. Complex structures such as dyke intrusions, severe faulting and folding offer further challenges to the application of seismic methodologies. Lack of deep boreholes and limited availability of sonic logging make interpretation of seismic data still more difficult.

Each of the above issues has a systematic solution that begins with understanding the requirements of the final stage in analysis of the seismic data. The final stages of inversion and multi-attribute analysis require accurate structural image and consistent amplitude and phase information from the seismic responses. Accurate structural imaging is often difficult to achieve because of the regolith issues and unfavorable line-orientation with respect to the underground structures. Low signal-to-noise ratio, high ambient and source-generated noise and variable source and receiver coupling present serious challenges for preservation of true amplitudes. However, before any of these obstacles are addressed classifying relationships between seismic attributes and various rock types that are likely to host specific minerals are necessary. For that purpose an extensive "seismic response data base" needs to be derived from log measurements, core sample tests, and in-situ geological knowledge

INTRODUTION

Direct identification of various lithologies in contact from surface seismic data is a difficult but possibly very rewarding task. However this task is not straightforward; seismic exploration in hard-rock environments is generally difficult. Crooked seismic surveys are common in seismic exploration for mineral deposits due to mine-site and environmental restrictions. Limited exposure of Archaean rocks further complicate interpretation of geophysical data. In addition borehole information that can be used to calibrate seismic data are sparse and often restricted to shallow depths (200-900 m). While all these issues together create what initially appears to be an unsuccessful situation for seismic data inversion in hard rock environments, each challenge does have a systematic realistic solution.

Crooked seismic-line processing techniques are detailed by Nedimovic and West (2003) and in a more pragmatic and applicable way considered by the work of Urosevic and Juhlin (2007). The proposed actions however are inherently amplitude non-preserving and do not create a favourable condition for seismic inversion. Consequently, seismic inversion and multi-attribute analysis for rock characterisation is at present limited to instances where a minimum set of conditions is fulfilled: line in the dip direction, geology is 2.5 D, S/N ratio is satisfactory and seismic image is an accurate representation of the underground structures.

Forming an accurate, representative image in hard-rock environments is a difficult task. Image-gather analysis is typically hindered by low signal-to-noise ratio and out-of-plane events. Calibration of seismic data through FWS is rarely available, apart from the fact that logging in all-out hard-rock environments suffers from various problems. Finally the interrelationships among actual rock properties such as structure, alteration, lithology type, and their individual seismic responses are not unique. A site-oriented seismic inversion focuses the predictive possibilities by calibrating seismic data to borehole sonic log information, and to horizons as interpreted from seismic data to predict an earth model (Veire and Landro, 2007). The predictive nature of inversion is highly dependant upon the quantity and quality of the input data.

The attempts by multi-attribute analysis to link a set of seismic attributes to log properties appears more promising.

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These attributes include instantaneous attributes (Hilbert transform, amplitude envelope), windowed frequency attributes, filter slice attributes, derivative attributes, integrated attributes and time attributes (Hampson-Russell, 2007). With rigorous analysis, successful targeting of ore-bodies based on known rock types, structures, alterations, and potentially even gold content is possible.

Data preconditioning for inversion

In an attempt to form accurate images needed for further data analysis, Kirchhoff pre-stack depth migration (PSDM) was used (Pasasa et al, 1998). While this process is inherently amplitude non-preserving, several advantages including the ability to address irregular geometry and steep dips, plus the capability of performing under low signal-to-noise ratio, allow for successful application. Providing that an accurate velocity model is obtained from a combination of image-gather analysis, a priori geological information and log data, Kirchhoff depth migration could produce an accurate shallow subsurface image with negligible amplitude and phase distortions (Pasasa et al., 1998). For seismic inversion and multi-attribute analysis, the least or a minimal amount of data distortion is critical, especially with regard to shallow mining targets.

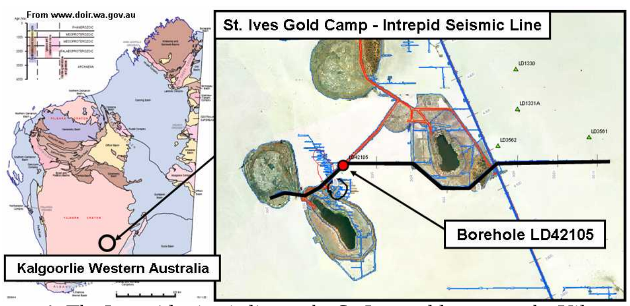

Figure 1: The Intrepid seismic line at the St. Ives gold camp on the Yilgarn block near Kalgoorlie in Western Australia is the focus of this study.

The Intrepid seismic line at the St. Ives gold camp in Western Australia was chosen as the test grounds for seismic prediction of the rock types (Figure 1.). The St. Ives gold camp is located on the Yilgarn block which represents an Achean craton, a hard rock environment consisting of granite-gneiss and metamorphosed sedimentary and volcanic rock. Due to line-crookedness, the Intrepid seismic line was partitioned into three segments in order to focus appropriate processing techniques onto each section. Figure 2 displays the selected line-segments including the flow used to optimize information retrieval from seismic data. In this segment, a borehole was available to assist in the creation of the best input-velocity model for PSDM. The final PSDM result shows a clearer image of the subsurface then the initial crooked-line seismic processing which revealed limited discernable reflections.

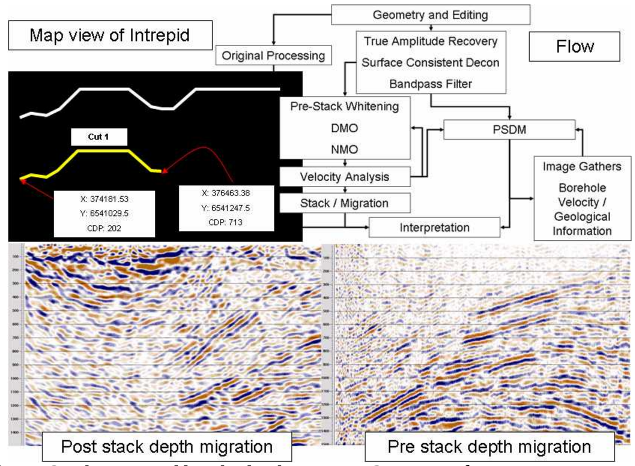

Figure 2: The Intrepid line had to be cut into 3 sections for appropriate processing, with the map view showing the first cut which is represented in this figure. The two processing flows for both post-stack and pre-stack areas are detailed in the upper right. Post-stack and pre-stack results show the advantageous use of pre-stack processing.

Borehole analysis

Correlation between seismic responses and rock types requires statistical data from rigorous borehole analysis resulting in a seismic response catalog. With proper conditioning full waveform sonic (FWS) logs (P-wave, S-wave and density) from borehole data present the possibility of response identification on seismic data through the use of synthetic response along the borehole. A methodical approach to investigating these synthetic responses from borehole logs and also various attributes derived from the synthetic is required to discover a statistical basis for lithology predictions. Multiple boreholes drilled to a target depth and logged with FWS significantly enhance the analytical ability of lithology prediction. Unfortunately, in hard rock environments, borehole data with FWS are sparse.

A single deviated borehole with FWS logs drilled to 1000 meters on the Intrepid seismic line (Figure 1) provided data for correlation with seismic data and statistical analysis. A 50 Hz Ricker wavelet was initially chosen to generate a synthetic seismic line along the log to observe potential responses from lithological contacts. Figure 3 displays the resulting synthetic responses from the Zeoppritz calculations (Yilmaz, 2001), from zero to 500 meter offset.

The synthetic response shows the angle-dependent amplitude variation or AVO (amplitude versus offset) (Yilmaz, 2001). These variations (or the gradient) have some potential in identification of reflectivity patterns of lithology. The gradient was cross-plotted with P-wave, S-wave and density information to establish trends for various rock types in contact. Those trends were used to re-create a hidden log (Vs, or density). Finally the new synthetic was computed (Figure 4) which then allowed for comparisons to the original data in Figure 3. This procedure was a test-ground for wider application of empirical rock-property trends.

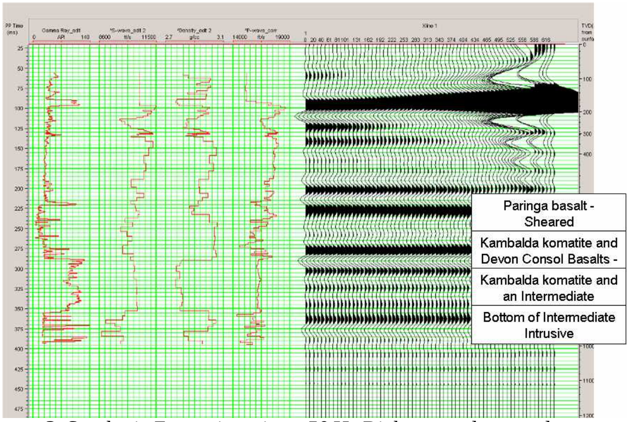

Figure 3: Synthetic Zeoppritz using a 50 Hz Ricker wavelet reveal responses on several major interpreted contacts along the borehole.

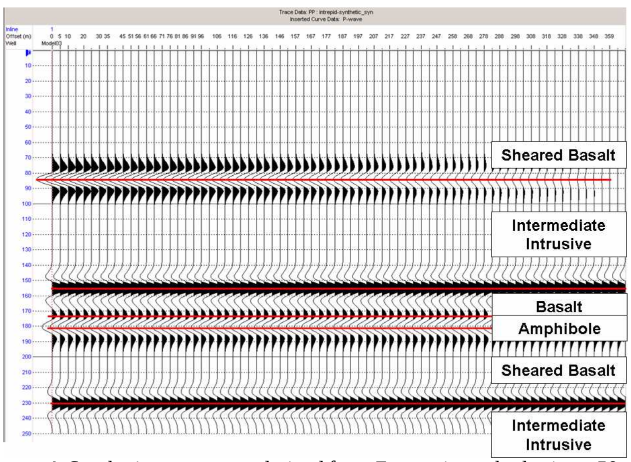

Figure 4: Synthetic response as derived from Zeopprtiz method using a 50 Hz wavelet on rock characterization from cross plot analysis.

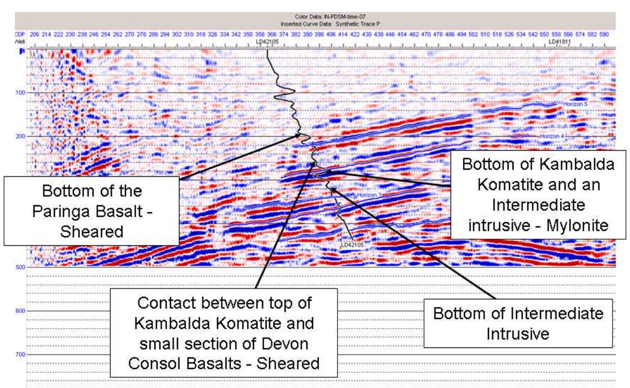

Figure 5: Synthetic seismogram inserted into the seismic data. After correlation the main contacts can be traced.

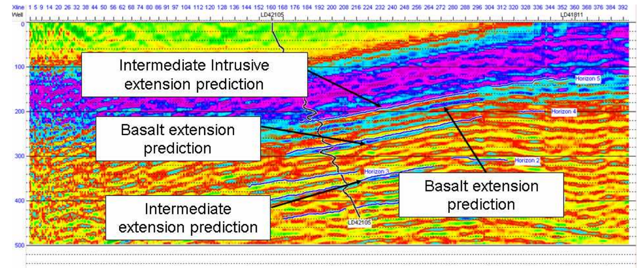

Figure 6: Model inversion of the Intrepid seismic line. A reasonably good prediction of the rock types in contact is achieved despite numerous assumptions inherent in the process. The dark colours represent significant high responses in the impedance prediction which in this case correspond to a shear-zone through a basalt formation. Extensions of contacts can also be seen throughout the inversion.

While the synthetic response does represent idealized conditions, the results from both the log and empirical trends indicate reducible statistical correlations with identifiable existing lithologies.

Seismic inversion

Analysis of the FWS logs from the borehole has indicated that physical characteristics of rock-type and shear-zone properties can be matched with synthetic responses derived from empirical trends.

The objective of the inversion process is to link the recovered acoustic impedance, through the empirically derived trends to various lithologies in contact. Inversion predictions however, suffer from non-uniqueness based on possible multiple geological models, processing errors, low S/N ratio, lack of check-shot(s) availability, logging errors, wavelet distortions and poor log-seismic correlation. The reliability of inversion results increases with the number of constraints (logs) used in the process.

Utilizing the empirically derived trends, a wavelet was statistically extracted to create a synthetic seismogram. In order to improve the log-to-seismic correlation, the log data needed to be stretched, particularly since check-shot data was unavailable. After several iterations, cross correlation of 0.6537 was achieved between the synthetic and seismic. The main contacts were subsequently selected as shown in Figure 5.

A model-based inversion was chosen for this seismic data. The model can be constrained with both hard or soft conditions. The frequency was constrained to the dominant frequency of the seismic data. Figure 6 displays the inversions results.

The inversion has predicted potential lithological impedance-based responses through the entire seismic section. The basalt and intermediate intrusive contacts stand out in the impedance section. This initial result suggests that further constraints through multi-attribute analysis may provide even more accurate or more precise predictions of the underground lithology.

CONCLUSION

Difficulties with the application of seismic methods to hard rock environs do have systematic solutions. PSDM techniques have been shown to improve both image clarity and position, specifically on the Intrepid seismic line. An analysis of FWS data has shown that reasonable trends can be established between P-wave, S-wave, density and/or their combinations. Log-calibrated seismic images have potential for direct prediction of rock types. Further, inversion techniques have shown a potential for prediction of lithology.

The continued lack of full waveform sonic logs however, is a continuing hindrance to improved lithological interpretation in Western Australia.

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