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

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Summary:

The application of seismic methods in mineral exploration has increased in recent years in Western Australia. However unlike such applications in sedimentary environments, seismic exploration in hard rock environments has proven, to date to be cumbersome. Difficulties commence with issues related to data acquisition including such factors as remote mine site locations, ruggedness of terrain, and environmental restrictions have resulted in seismic lines being misaligned with dominant geological 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 applications of seismic methodologies. Lack of deep boreholes and a seldom use of sonic make interpretation of seismic data even 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 end 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 hard 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 is addressed it is necessary to classify relationships between seismic attributes and various rock types that are likely to host specific minerals. For that purpose an extensive "seismic response data base" need to be derived from log measu*rements, core sample tests and in-situ geological knowledge*

Introduction:

Direct identification of various lithologies in contact from surface seismic data is a difficult but possibly very rewarding task. However this task of seismic application in hard rock environments is not as straightforward as seismic exploration in hydrocarbon environments. The traditional cornerstone of accurate seismic surveys is the positioning of seismic lines in straight lines. However, crooked seismic surveys are common in seismic exploration for mineral deposits in hard rock environments due to mine-site and environmental restrictions. Limited exposure of Archaean rocks further complicates 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 unlikely situation for successful seismic data interpretation 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 in Urosevic and Juhlin (2007). However the proposed actions are inherently amplitude-non-preserving and do not create a favourable ground for seismic inversion. Consequently seismic inversion and multi-attribute analysis for rock characterisation is an accurate seismic fingerprint of the underground structures only where a minimum set of conditions is fulfilled: line in the dip or shear direction, geology of 2.5 D, satisfactory S/N ratio. Forming an accurate, representative seismic fingerprint in hard rock environments is a difficult task. Image-gather analysis is typically hindered by low signal-to-noise ratio, out-of-plane events, and the dirth of accurately calibrated seismic data through FWS.

Also, the relationships between actual rock properties such as structure, alteration, lithology type, and their seismic responses are not unique. A site-oriented seismic inversion focuses the predictive possibilities by calibrating seismic data to borehole sonic log information, and horizons interpreted from seismic data to predict an earth model (Veire and Landro, 2007). The predictive nature of inversion is highly dependant on quantity and quality of data.

Multi-attribute analysis appears more promising as it attempts to link a set of seismic attributes to log properties. 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 multi-attribute analysis of further characteristics including known rock types, structure, alteration, and potentially even gold content, the seismic targeting of ore bodies can be possible. However, the wealth of information is related to the predictive ability of multi-attribute analysis.

Data preconditioning for inversion

For seismic inversion and multi attribute analysis, the least amount of data distortion is critical, especially with regards to shallow mining targets. In an attempt to form accurate images as needed for the further data analysis the researchers used Kirchhoff pre-stack depth migration (PSDM). While this process is inherently amplitude non-preserving, several advantages are noted such as capacity for handling of irregular geometry, e.g. steep dips, and the capability of performing under low signal-to-noise ratio. Kirchohoff depth migration, could produce an accurate shallow subsurface image with negligible amplitude and phase distortions (Pasasa et al., 1998) providing that an accurate velocity model is obtained from a combination of image gather analysis, a priori geological information and log data,

The Intrepid seismic line, at the St. Ives gold camp in Western Australia, was chosen as the testing grounds for seismic prediction of the rock types. Due to the crookedness of the Intrepid seismic line, the data was partitioned into three segments to focus appropriate processing techniques onto each section. Figure 1 displays the selected line segments, including the flow, used to optimize information from seismic data. In this segment, a borehole was available to help in creation of the best input-velocity model for PSDM. The final PSDM image is a clearer image of the subsurface than the initial crooked line seismic processing image which actually revealed limited discernable reflections.

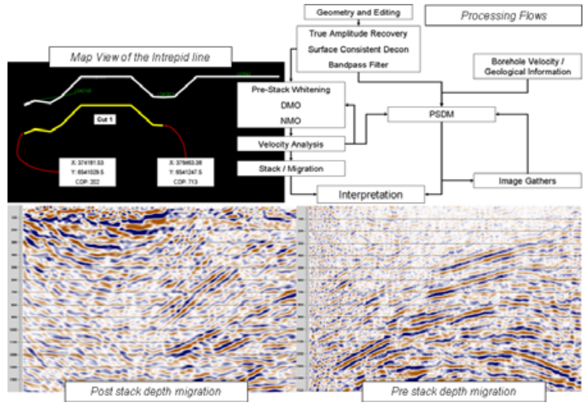

Figure 1. The Intrepid line had to be cut into 3 sections for appropriate processing, with the map view showing the first cut which is represented in this figure. The two processing flows for both post stack and pre stack area are detailed in the upper right. Post stack and pre stack results show the advantageous use of pre stack processing.

Borehole analysis

A correlation between seismic responses and rock types requires statistical basis from rigorous borehole analysis known as 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 (Lines & Treitel, 1984). To reveal a statistical basis for lithological predictions, investigation of synthetic responses from borehole logs, and an attribute analysis of these same borehole data, is required Multiple boreholes with FWS logs drilled to a target depth enhance the analytical ability of lithological predictions. 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 was available for correlation with seismic data and multi-attribute statistical analysis. A 60 Hz Ricker wavelet was initially chosen to generate a synthetic seismic line along the log to observe potential responses from lithological contacts. Figure 2 displays the resulting synthetic responses from the Zeoppritz calculations from zero to 500 meter offset.

Seismic methods for mining in Western Australia

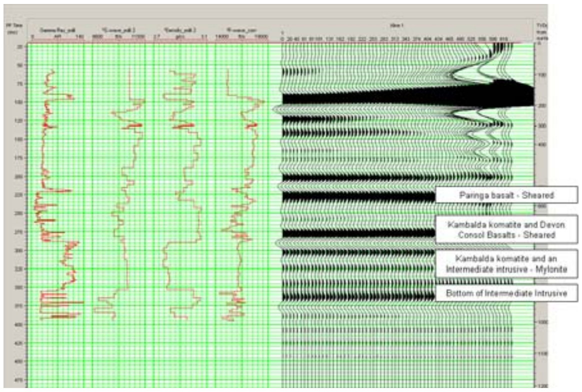

Figure 2. Synthetic Zeoppritz using a 60 Hz Ricker wavelet reveal responses on several major interpreted contacts along the borehole.

Synthetic response shows the angle-dependant amplitude variation (AVO) (amplitude versus offset). This variation (or the gradient) has some potential in the identification of reflectivity patterns of lithology. Then the researcher's cross-plotted P-wave, S-wave and density information to establish trends for various rock types in contact. Those trends were applied to re-create a "hidden" log (Vs, or density). Finally, the "new" synthetic was computed (Figure 3) thus providing a comparison to the original in Figure 2. This "procedure" was a test ground for a wider application of empirical rock-property trends.

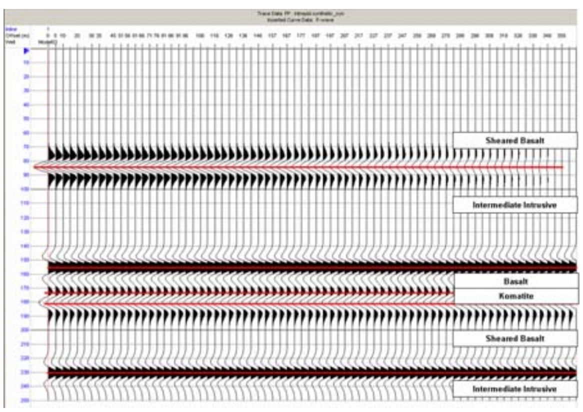

Figure 3. Synthetic response as derived from Zeopprtiz method using a 60 Hz wavelet on rock characterization from cross plot analysis.

While the synthetic does represent idealized conditions, the results from both the log and empirical trends indicate reducible statistical correlations with 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 seismic inversion process is to link the "recovered" acoustic impedance, through the empirically derived trends, to various lithologies in contact. Inversion predictions suffer from non-uniqueness based on possible multiple- geological models, processing errors, low S/N ratio, no check-shots available, logging errors, wavelet distortions and poor log-seismic correlation, therefore the reliability of inversion results increases with the number of constraints (logs) used in the process.

In the next step, the researchers used the empirically derived trends and statistically extracted wavelet to create synthetic seismogram. To achieve a significant correlation between the synthetic seismic data and borehole sonic log information the log data required manipulation particularly when check shot data is not available. After several iterations, a cross correlation of 0.6537 was achieved between the synthetic and seismic. The main contacts were subsequently picked (Figure 4).

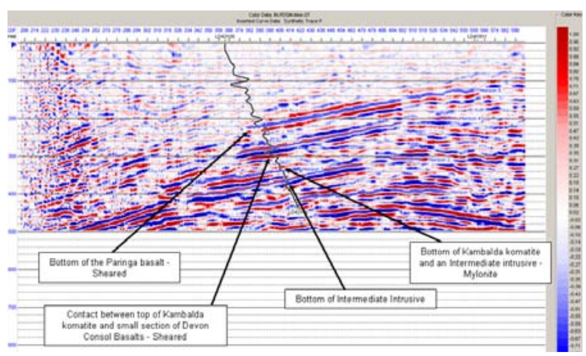

Figure 4. Synthetic seismogram inserted into the seismic data. After correlation the main contacts can be traced.

A model-based inversion was chosen for this seismic data. The model-based inversion can be constrained with hard or soft conditions. The frequency was constrained to the dominant frequency of the seismic data. Figure 5 displays the inversions results.

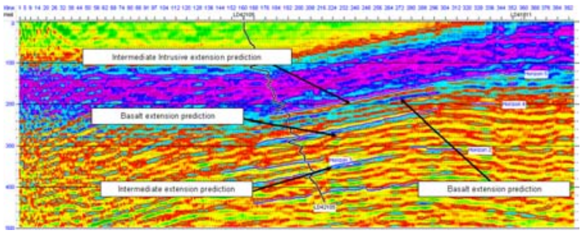

Figure 5. Model inversion of the Intrepid seismic line. A reasonable prediction of the rock types in contact is achieved despite numerous assumptions in the process.

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 positive predictions of the underground lithology.

Conclusion

Difficulties in hard rock seismic method, while numerous, appear to have systematic solutions. PSDM techniques have shown to improve both image clarity and position, on the Intrepid seismic line. An analysis of FWS data have 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. Inversion techniques have further shown potential for prediction of lithology.

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

EDITED REFERENCES

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REFERENCES

Bradford, J. H., L. M. Liberty, M. W. Lyle, W. P. Clement, and S. Hess, 2006, Imaging complex structure in shallow seismic-reflection data using prestack depth migration: Geophysics 71, no. 6, B175–B181.

Calderon, J. E., and J. Castagna, 2007, Porosity and lithologic estimation using rock physics and multi-attribute transforms in Balcon Field, Colombia: The Leading Edge, 26, 142–150.

Hampson-Russell, 2007, Guide to Emerge: PDF in the Hampson-Russell software package.

Hart, B. S., 2002, Validating seismic attribute studies: Beyond statistics: The Leading Edge, 21, 1016–1021.

Hawman, R. B., C. L. Prosser, and J. E. Clippard, 2000, Shallow seismic reflection profiling over the Brevard zone, South Carolina: Geophysics, 65, 1388–1401.

Pasasa, L., F. Wenzel, and P. Zhao, 1998, Prestack Kirchhoff depth migration of shallow seismic data: Geophysics, 63, 1241–1247.

Reed, L. E., M. F. Taner, B. E. Elliot, and P. G. Killeen, 1997, A comparison of physical properties borehole logs with geology, mineralogy and chemistry in a borehole at Les Mines Selbaie, North-western Quebec, Canada: Geophysics and Geochemistry at the Millennium, 1043–1048.

Stuart G. W., S. J. Jolley, L. G. B. T. Polome, and R. F. Tucker, 2000, Application of 3D seismic attribute analysis to mine planning: Target gold deposit, South Africa: The Leading Edge, 19, 736–742.

Urosevic, M., and Julin, C., 2007, An analysis of seismic information obtained from crooked line seismic surveys in crystalline rocks, Australia: 69th Conference and Exhibition, EAGE, Extended Abstracts.

Veire, H. H., and M. Landro, 2006, Simultaneous inversion of PP and PS seismic data: Geophysics, 71, no. 3, R1–R10.