Integrated fault interpretation using well data

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SUMMARY

A standard well logging suite, including borehole seismic, sonic and formation imaging data logged in 2011 on the North-West Shelf of Australia, is shown to provide crucial structural interpretation information when processed in an innovative and integrated way. Initial well logging results indicated that the pre-drill seismic interpretation model was not matching the observations. Geological information from wireline borehole resistivity imaging tools confirmed the presence of many fractured/faulted zones in the well and synthetic seismograms showed that there was a problem tying well information to the surface seismic markers. The acquired rig source vertical seismic profile (VSP) established a good time-depth relation as well as a tie with the other log data. Further analysis of the three component VSP data showed significant and anomalous out of plane seismic events resulting in the proposal of a novel fault analysis workflow. A calibrated 2D model was built and a combination of modelling and VSP dip estimation techniques were used to provide solid indications of a major steeply dipping fault cutting the wellbore. Sonic and borehole imaging data were subsequently analysed providing further support for this interpretation. By combining the processing results of various petro-technical domains, a coherent and integrated fault interpretation was obtained that significantly altered the initial perception regarding a major fault position and its well intersection. A new 3D interpretation effort is now being undertaken as a result of these new findings. This project demonstrates the value of integration of data processing and interpretation.

Key words: Borehole Seismic, VSP, Fault, Interpretation, Imaging

INTRODUCTION

When drilling for hydrocarbons exploration companies routinely acquire many different down-hole measured datasets to help piece together the complex story that describes the reservoir. Often these individual measurements provide valuable information on their own. However, integrated processing and interpretation of these measurements provide additional information that can significantly impact the way a coherent reservoir interpretation is constructed. This paper describes a case study where integrated analysis of well data resulted in an improved seismic fault interpretation.

A vertical exploration well was recently drilled on the North-West Shelf of Australia (Figure 1) targeting oil in Jurassic reservoir sands in an up-dip fault block in the Dampier sub-basin of the Northern Carnarvon Basin (Geoscience Australia, 2010). A full wireline logging suite was acquired including borehole resistivity imaging (FMI), sonic and borehole seismic (VSP) services for use in post-well analysis.

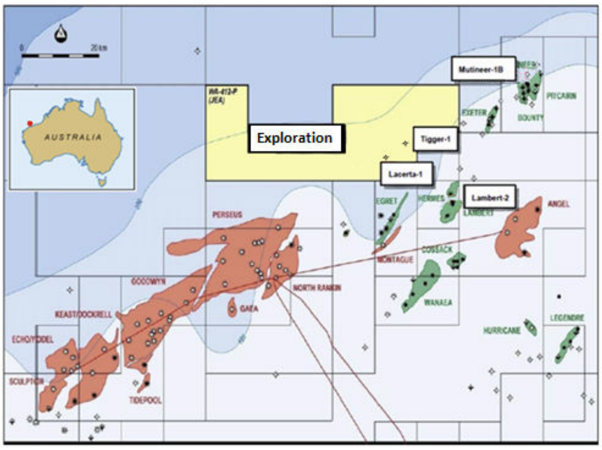

Figure 1. Location map showing geographical area

Initial well logging results indicated that the pre-drill seismic interpretation model was not matching the observations as shown in Figure 2. The geological information from a wireline resistivity imaging tool (FMI) indicated significant cross bedding and fractured/faulted zones in the well and there was little confidence in the established formation tops. Quick-look synthetic seismograms also showed that there was a problem tying well information to seismic markers.

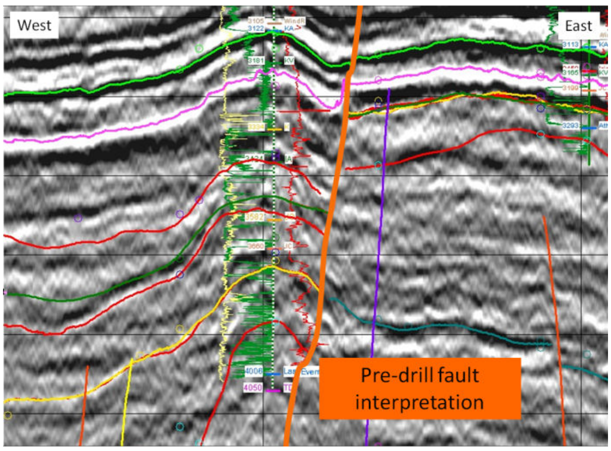

Figure 2. Pre-drill seismic fault interpretation

While sonic (DSI) and FMI information were still being processed, QC processing of the acquired borehole seismic Vertical Seismic Profile (VSP) survey showed that anomalous events were visible on the three component data (Figure 3) affecting the data quality and indicating structural complexity. Comprehensive VSP processing was undertaken to further investigate these events and extract as much information out of the VSP as possible.

Data from three different petro-technical domains were subsequently processed and analysed to obtain a coherent interpretation on the position and orientation of a possible major seismic scale well-intersecting fault.

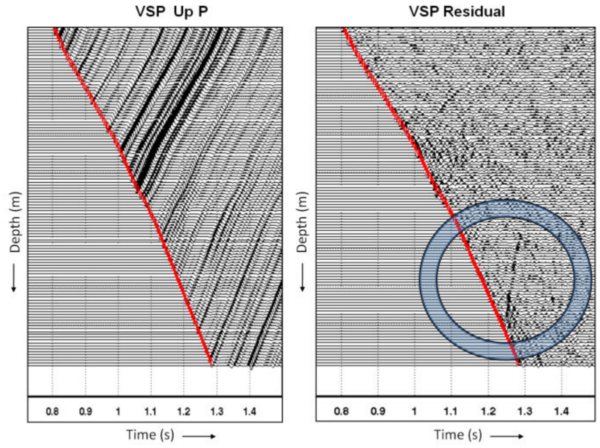

Figure 3. VSP wave fields showing anomalous events

METHOD AND RESULTS

Different disciplines, one solution

None of the individual disciplines was able to independently provide a complete answer to solve the many conflicting and unknown interpretation aspects and it was clear that collaboration was needed. Much can be gained from combining the processed information and the following describe the results obtained from each discipline.

Geophysics: Borehole Seismic

A rig source VSP survey was carried out in the near vertical exploration well. The main objectives of the survey were acquisition of a vertical check-shot velocity profile (Time/Depth relation) and a VSP dataset for generation of a corridor stack and well to seismic calibration. These objectives were achieved using standard VSP processing techniques (Pereira and Jones, 2010). Depth matching between the VSP corridor stack and the time-migrated surface seismic 2D in- and cross-line sections through the well location was performed and a mildly time variant match was obtained.

Analysis of the 3 component VSP data showed that in the deeper part of the well, anomalous events were present in the data, as opposed to the normally expected up or down-going direct arrivals or formation reflections.

Further study of these events was carried out and a Fault Plane Analysis workflow was subsequently established:

Pre-Processing / 3C Rotations
Velocity Model Building
Ray tracing Modelling
VSP Dip Estimation

Although not in the standard scope for rig source VSP processing, a quick calibrated 2D velocity model of the subsurface was built for the following reasons:

- VSP ray tracing modeling to help under-stand various ray modes in the subsurface
- Determine the move-out of possible fault plane reflections visible in VSP data

This simple structural model was initially built from a VSP calibrated and blocked 1D model of vertical Vp, Vs and Density and was constructed then in 2D using the depth converted seismic line. The actual horizons in depth are based on a combination of well tie information, structural dip and surface seismic interface picking.

This initial model was subsequently calibrated using ray-tracing and travel time inversion with constant velocity layers and the real VSP travel time information as shown in Figure 4.

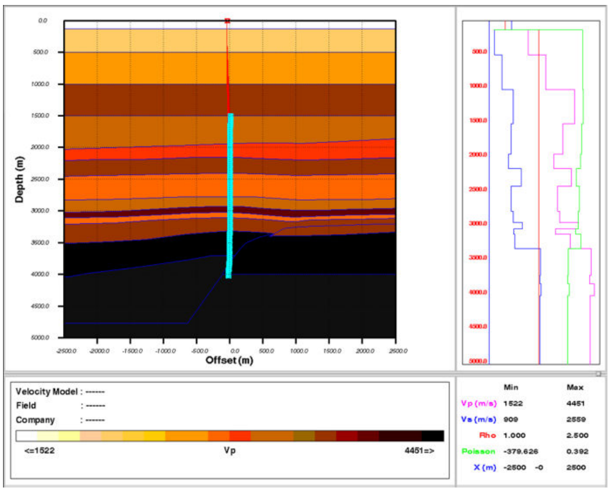

Figure 4. 2D VSP calibrated model

Ray tracing modelling was done, iteratively changing dip and depth of a fault plane intersecting the deeper part of the well, while comparing modelled move out of such a reflection event and real VSP data. These results indicate that a fault plane reflection event with a lower dip (30 or 45 degrees) is not steep enough to explain the move out of this anomalous event on the real data. Optimal results are obtained with a fault plane dipping approximately 55 degrees and intersecting the wellbore around 3845 m TVD MSL.

This fault plane reflection would be composed of a compressional (P) reflection mostly recorded on the horizontal component and a converted shear (PS) reflection, mostly recorded on the vertical component data. This can be understood by looking at the modelled ray paths and diagram in Figure 5.

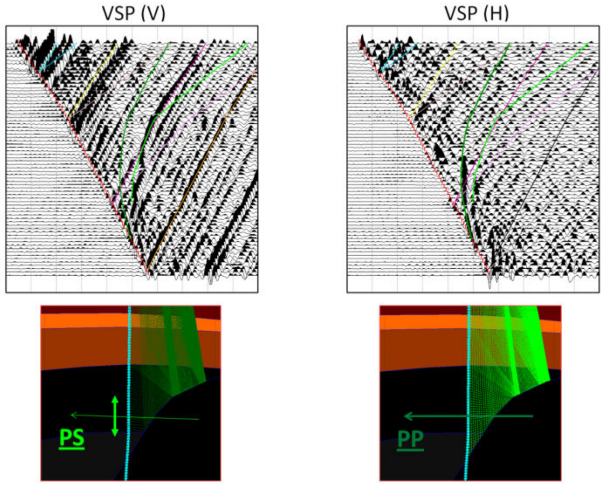

Figure 5. Modelled fault reflection vs. actual VSP vertical and horizontal component data

To provide further confidence in the estimated fault plane dip values, dip compensating NMO was applied to the VSP up-going wave field. By calculating the dip spectrum and performing the move-out flattening using various dip values, it can be seen that higher dip values in the order of 55 deg are required to flatten the fault reflection close to the wellbore as shown in Figure 6.

The interpreted dip value of 55 deg can be used as a minimum dip value as it is possible that, due to the 3D nature of the well trajectory (dipping mostly towards the north-west) versus the fault orientation, the obtained value is an apparent dip and therefore underestimating the true dip of a differently oriented plane.

Also both the modelling and dip compensating NMO approaches seem to indicate that the steep dip of such an event may be flattening slightly shallower and away from the wellbore.

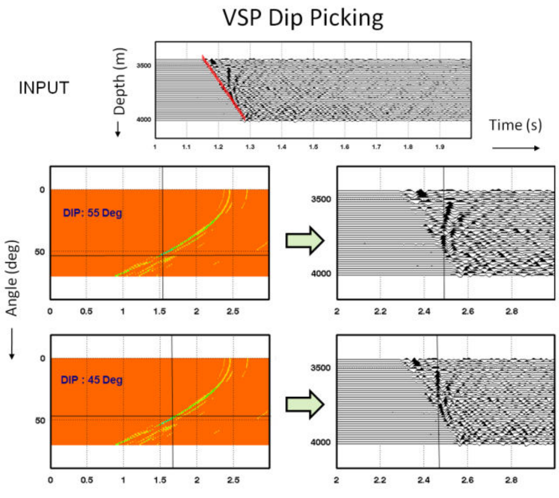

Figure 6. Dip estimation from VSP data

Petrophysics: Sonic Slowness

A Dipole Shear Sonic Imager (DSI) survey was logged in this exploration well. The main objective of this survey was recording high quality sonic compressional and shear slowness curves as input for petro-physical, geo-mechanical and geophysical applications.

Sonic monopole waveforms were processed to obtain a compressional slowness curve that was subsequently calibrated to the previously mentioned VSP data. Synthetic seismograms were generated from the calibrated sonic and density curves by calculating acoustic impedance and reflectivity followed by a convolution with a known zero phase wavelet.

Analysis of these synthetic seismograms (Figure 7) shows that there is an excellent match between the VSP and Synthetics apart from a small section just below the newly interpreted well intersection of this major seismic fault. This anomaly is caused by differences in ray paths, frequency and material properties and further strengthens the interpretation of a significant fault.

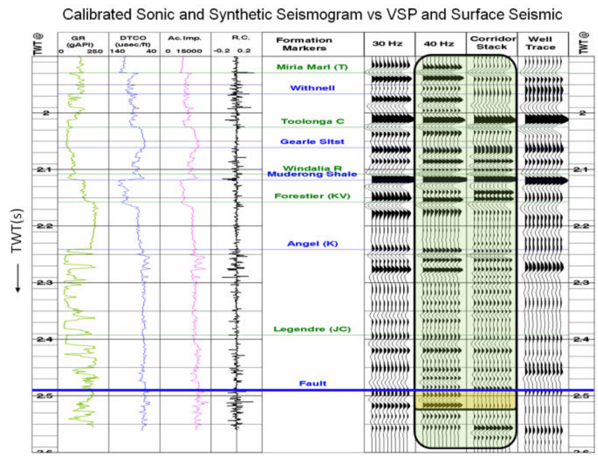

Figure 7. Sonic data provides further support for fault

Geology: Formation Imaging

An FMI (Formation Micro-Imager) image log was also acquired during wireline logging operations. The main objectives of the FMI acquisition were to obtain a micro-resistivity image of the borehole wall which would allow sedimentary and structural analysis of the geological strata intercepted by the well.

In addition to identifying facies and probable depositional environments, the sedimentary analysis determined formation tops using the image and palynology date results, found that a major source rock, the Dingo clay stone, was absent, providing a clue to the lack of hydrocarbon in the well.

In the structural analysis, twenty-two possible faults, and numerous natural fractures were identified in the image. The faults were evenly spread with depth along the image log, and strike mainly south-west to north-east, at typically moderate dip angle. Closer inspection found that changes in structural dip related to the position of some of these faults as shown in Figure 8.

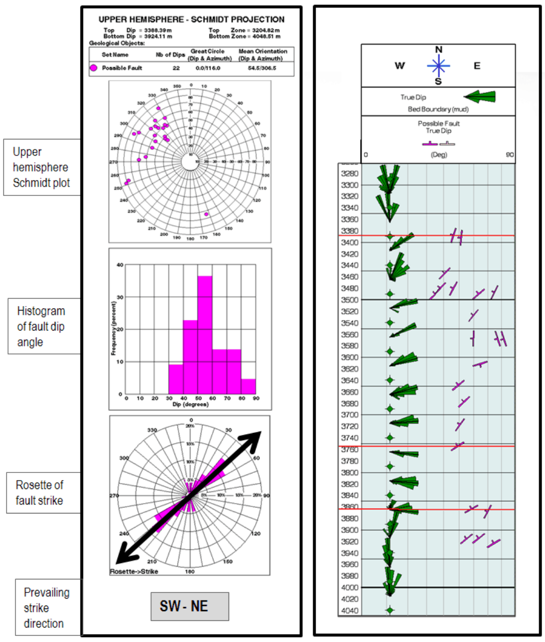

Figure 8. Summary of faults identified, and relation to structural dip changes

One of these faults at 3864 m MD (3841 m TVD MSL) was found to have caused the most dramatic change in structural dip (Figure 9), having rotated the dip direction of the bedding by 90deg and changed the dip angle of bedding by 10deg. The direction of movement of strata along this fault was not indicated on the image; however, the moderately high dip angle (58deg) of the fault is typical of normal fault movement.

Furthermore, bedding offset visible on other faults identified, and the moderately high dip angle of most faults suggest normal faulting to dominate in the system.

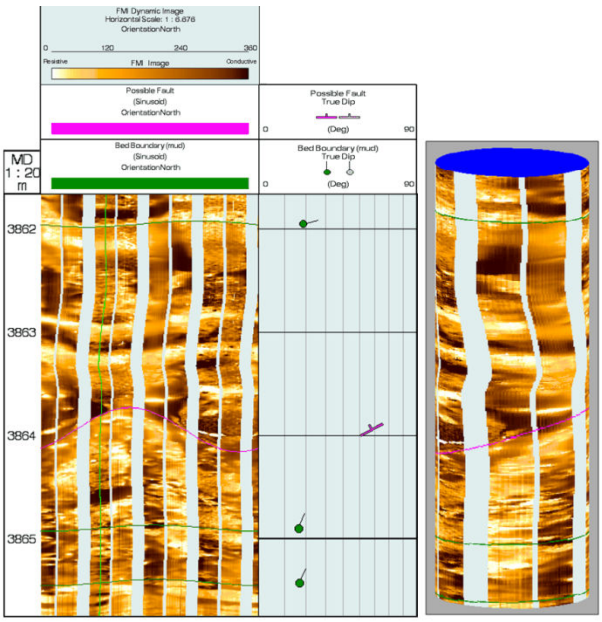

Figure 9. FMI image, displaying the major fault

By themselves the many visible fault and dip measurements provided useful information, however together with the previously discussed results from the borehole seismic and sonic data a more comprehensive and powerful interpretation became possible.

CONCLUSIONS

This study shows that by integrating the processing results of various petro-technical domains, a coherent interpretation can be obtained.

By combining a novel borehole seismic approach to analyse fault plane reflections with a comprehensive borehole geology analysis and sonic information, a strong case can be made for the presence of a major steeply dipping seismic scale fault crossing the wellbore.

This integrated result significantly altered the pre-drill perception regarding fault position and its well intersection. A new 3D interpretation effort is now being undertaken as a result of these new findings.

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