Multi-Azimuthal Walkway VSP for Full Azimuth Seismic Calibration

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SUMMARY

Comprehensive borehole seismic surveys hold the key to unlocking the knowledge contained within the long-offset full-azimuth surface seismic surveys that are fast becoming common in land exploration. This paper presents a case study of acquisition, processing and use of such survey for validation and calibration of processing parameters and inversion results of a recent point-source/point-receiver 3D surface seismic dataset acquired in the Cooper Basin.

The 3D surface seismic data have been initially processed without significant borehole seismic data input. However, as the processing revealed gaps in knowledge, the need for borehole calibration was realised. This led to acquisition of a complex borehole seismic survey in a gas-discovery well comprising Multi-Azimuthal Walkaway (MAZ WVSP), Walkaround and Zero Offset Vertical Seismic Profiles (ZVSP). The acquired dataset shed light into the peg-leg multiple mechanisms as well as the VTI and azimuthal anisotropy. Advanced processing techniques such as calibrated piece-wise VTI inversion and azimuthal travel time fitting were applied to the MAZ WVSP data to validate the processing steps of the 3D surface seismic data and calibrate the results of its AVOaz inversion.

Apart from showing some of the results of this study, this paper documents the various contact points between VSP and surface seismic datasets and how the results of processing complement each other. The final result comprised a calibrated seismic map of drilling targets.

Key words: MAZ Walkaway, VSP, azimuthal anisotropy, FAZ seismic, drilling targets.

INTRODUCTION

The Cooper Basin provides a fascinating mix of both conventional and unconventional resources. Whilst the conventional resources are well documented, exploration companies are looking for more efficient ways to unlock the region's unconventional gas and oil potentials. Due to its complex depositional history, presence of clastic sediments, shales and coals, increasing attention is paid to improved target imaging and in particular de-multiple workflows and azimuthal AVO inversion of surface seismic data. The latter is one of the methodologies that has the potential to disclose evidence of fracture networks and/or induced stress regimes and location of sweet spots for drilling. A comprehensive borehole seismic (BHS) survey was acquired by SANTOS, a leading operator in Cooper Basin, in Kyanite-1, a recent condensate discovery well (partnered by Drillsearch, 2015). The aim of this acquisition was to aid the interpretation of the events and trends observed on the Munathiri 3D surface seismic survey, a recently acquired full azimuth (FAZ), longer offset 3D dataset. The BHS survey comprised a combination of Zero-Offset Vertical Seismic Profile (ZVSP), a Multi-Azimuthal Walkaway VSP (MAZ WVSP) and a Walkaround VSP.

Munathiri 3D is a point-source/point-receiver 3D FAZ surface seismic dataset that was acquired and processed to optimise vertical resolution and preserve azimuthal information using an azimuthal PreSTM methodology. The major challenges associated with processing this survey were the presence of interbed multiples across the zone of interest and poorly understood seismic anisotropy in both Horizontal Transverse Isotropy (HTI) and Vertical Transverse Isotropy (VTI) senses. It was recognised that well information was needed to provide detailed information on multiple generators, to improve multiple attenuation workflow. Interbed multiples were studied using the acquired ZVSP , identifying the major interbed multiple generating surfaces(Galybin *et.al*, 2010). A separate study documenting the application of those results is currently in preparation, and will not be covered here.

The need for preservation and analysis of azimuthal information is important as there are two sets of natural fractures and two sets of faulting observed within the target unconventional resource play of the Roseneath and Murteree shales (Abul Hair, *et el.*, 2012; Ahmad and Haghighi, 2012), which may influence the productivity at any given location. The fractured nature of a reservoir has a direct link with seismic velocity *i.e.* azimuthal anisotropy (Miller and Spencer, 1994; Gretchka and Tsvankin, 1999). A number of studies (such as Grimm et al., 1999) have shown that surface seismic data can be used to extract a fracture related attribute from wide-azimuth surface seismic data. However these data need to be calibrated to and validated against, the borehole measurements before a reliable attribute map can be derived (Breton and Cadoret, 1997). Leaney *et al.* (1999 (1)) have demonstrated a method to extract meaningful fracture information from MAZ WVSPs in conventional reservoirs. This paper shows how to apply this method to an unconventional reservoir to link it with surface seismic azimuthal Amplitude Versus Offset (AVOaz) inversion.

METHOD AND RESULTS

Full-azimuth surveys (FAZ)with longer offsets, offers improved illumination, improved reflection angle sampling, and signal-to-noise ratio over the standard narrow-azimuth surveys (NAZ) . The more symmetrical azimuthal sampling of FAZ surveys offers the opportunity for azimuthal AVO inversion that can lead to identification of fracture networks within the subsurface (Gretchka, 1999). Munathiri 3D was acquired in this mode to investigate both conventional and unconventional targets of the Cooper Basin at depths of over 2000 m. It was processed through an inversion ready workflow using the application of a multi-dimensional interpolation technique and multi-azimuth processing to generate individual azimuth/angle stack volumes as input for azimuthal inversion and for final full stack image creation (Poole *et al.*, 2015). Well calibration and validation was required to aid the interpretation of the azimuthal attributes generated by AVOAz inversion such as slow and fast shear velocity directions. A MAZ WVSP is ideally suited to measure velocity anisotropy in both Vertical Transverse Isotropy (VTI) as well as Horizontal Transverse Isotropy (HTI) senses. However, estimation of these parameters is complicated by the effects of dip, overburden lateral velocity heterogeneity and near surface heterogeneity (statics).

A MAZ WVSP was designed and acquired in Kyanite-1, in the Western Patchawarra Trough using broad band 2–180Hz maximum displacement sweep (Bagani, 2008) with an AHV-IV Commander vibrator as seismic source (Figure 1). The dataset was acquired using a 20 level VSP tool (VSIT-G, 15.24 m inter-shuttle spacing) in 3 settings anchored in the 1975 – 2873 m TVDMSL interval, resulting in 60 WVSP levels. Four WVSP lines were acquired at 20°, 65°, 110° and 155° azimuth from North with maximum offsets reaching ±4.5 km.

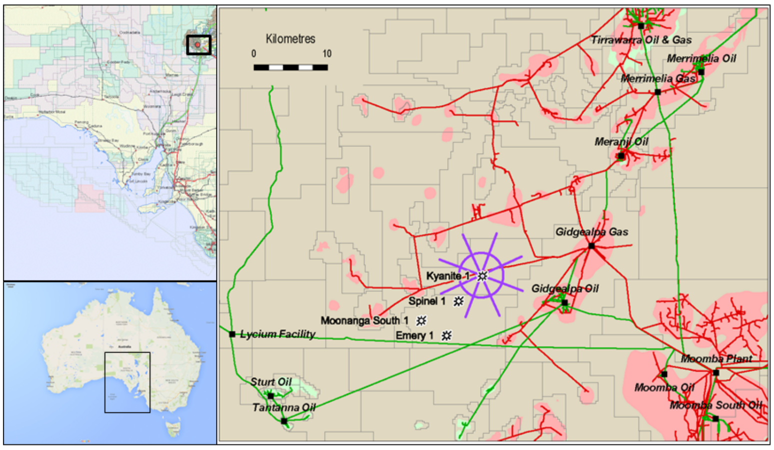

Figure 1. Kyanite-1 Well Location (courtesy of Santos, SARIG and Google)

The first key challenge for MAZ WVSP surveys on land is derivation of near surface statics corrections. These can be broken down into elevation statics and source residual statics. The surface velocity was measured by the ZVSP survey from ground level to the reference datum (in this case MSL) and applied as elevation statics to the MAZ WVSP data. The remaining source statics were determined by fitting a 6th order polynomial through the elevation-corrected travel times for each receiver and taking a median of the differences. These statics varied for each 20-level setting because the data were acquired at different times of day and slightly varying surface locations. Evaluation of the source statics for deep, intermediate and shallow settings showed excellent correlation of source statics and virtually no correlation with the elevation statics (Figure 2). The application of these statics subsequently improved the coherency of wavefields (Figure 3) and a stable result for the 1D VTI inversion (Leaney *et al.*, 1999(1)) and HTI inversion (Leaney *et al.*, 1999 (2)).

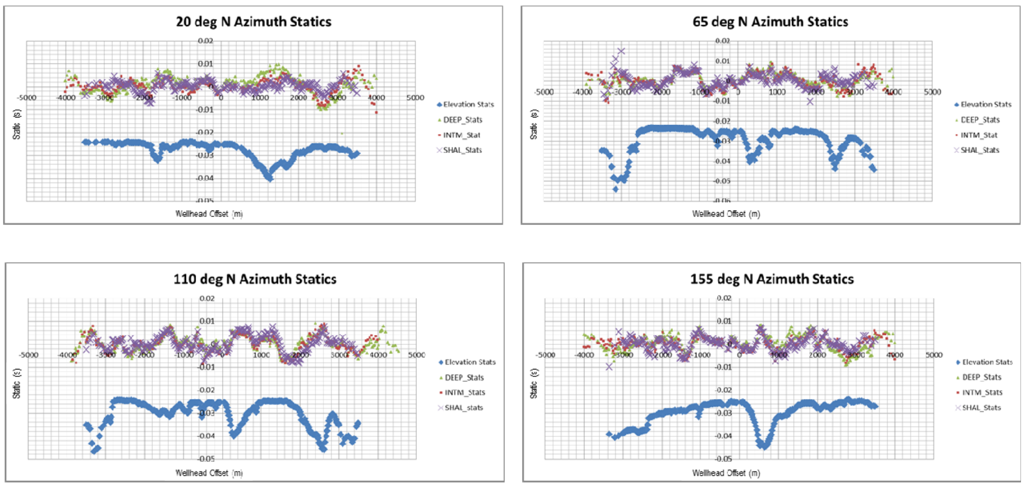

Figure 2. WVSP Elevation and Secondary Residual Source Statics

The 1D VTI Anisotropy inversion was performed on a line-by-line basis. The inital 1D models comprised ZVSP measured compressional velocities, extracted shear velocities and density measurements blocked with a minimum of 15m Backus averaging criteria with additional interfaces to preserve coal lamination. The inversion results are 1D travel time models, forg each acquisition azimuth, from surface to bottom of the receiver array. To estimate anisotropy above the receiver array a product of Vp/Vs and a compaction trend, derived using the measured Vp, was taken (after scaling from 0 to 1) as a guide. For the interval containing the WVSP receivers above the Roseneath, Epsilon and Murteree (collectively known as REM) and the Patchawarra interval, Vp/Vs ratio was used. The inversion in the coals was stable for the Thomsen ε parameter, but not sensitive to Thomsen δ. Hence slowness-polarisation analysis and inversion results were used to provide VTI parameters in this interval. The resultant models (Figure 4, left) minimise transit time residuals (Figure 4, right) for each acquisition azimuth and are fully calibrated to the recorded waveforms. It should be noted that three distinct types of VTI behaviour were observed in sandstones, coal-bearing formations and shales (Figure 5).

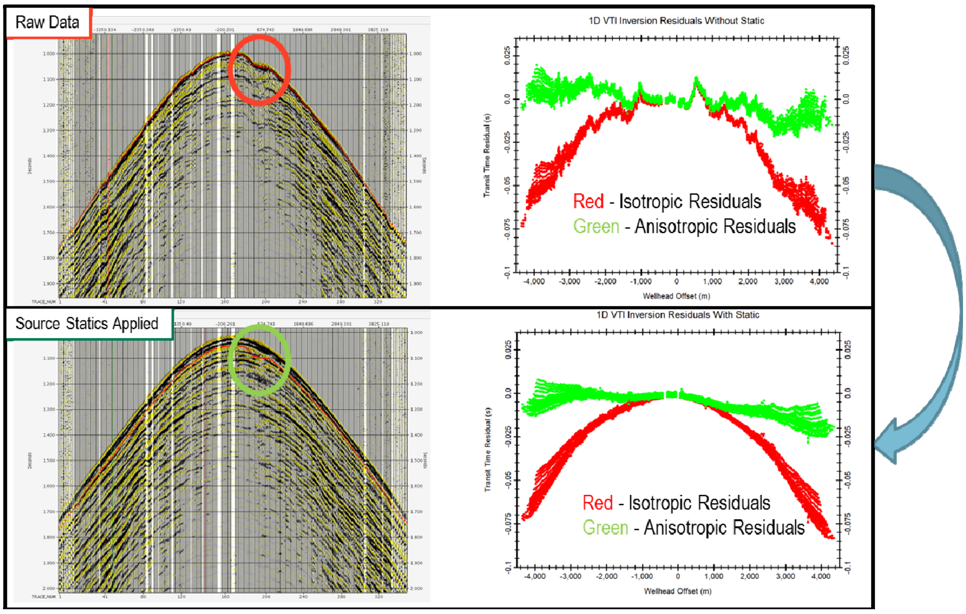

Figure 3. Effect on Smoothness of Wavefield and Transit Time Residuals for 1D VTI Inversion

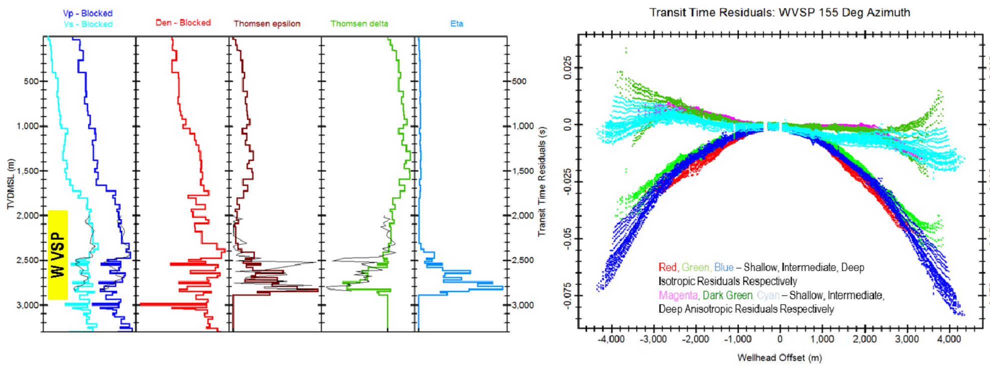

Figure 4. Left: 1D VTI model for 155°N Azimuth, the downhole tool setting is shown in yellow, thin black lines indicate the Slowness-Polarisation result; Right: Transit Time Residuals with isotropic and anisotropic models.

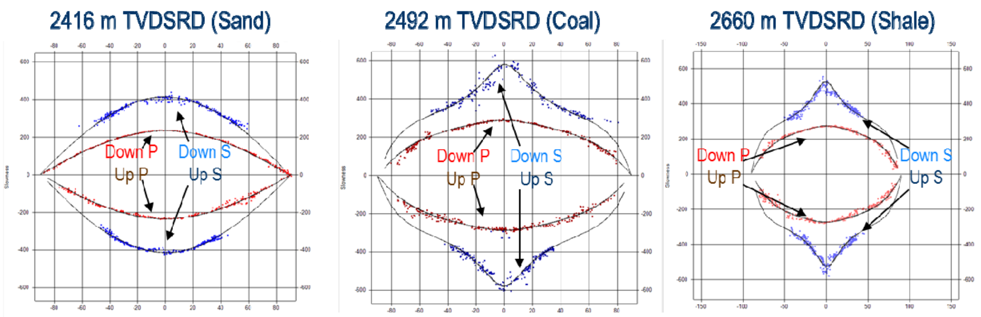

Figure 5. Slowness-Polarisation Cross-Plot for Sands, Coals and Shales (L-R).

The distinct behaviour of the slowness-polarisation cross plot for both downgoing and upgoing shear energy leaves little room for alternative explanation. The sands exhibit low levels of anisotropy, whilst coals and shales show large positive Thomsen's ε and negative δ. This result is further strengthened by a recent study performed by Pevzner *et al.* (2014), which also showed significantly negative Thomsen δ functions in another well in the basin, Encounter-1.

Estimation of the azimuthal ansisotropy variation (HTI) can be performed by a number of methods and the primary method used here is direct compressional travel time fitting using a polynomial function of the 7th order. Leaney *et al.* (1999 (2)) have showed that both direct and reflected energy can be used in a conventional reservoir. However due to the thinly-laminated nature of the coal reservoirs and presence of interbed multiples, it was not practical in this case to use reflected energy. Hence, only direct travel times are used for estimation of azimuthal anisotropy. These direct travel times, after static corrections are fitted, for each receiver, by a 3D polynomial containing effective dip and effective azimuthal variation terms. Displaying the HTI fitting results as a mis-fit map surface in interpretation software like Petrel© (Figure 6) allows visualization of effects of azimuthal anisotropy on compressional travel times for key horizons.

Another level of integration between borehole and surface seismic surveys for this project is the validation of the AVOaz behaviour by the MAZ WVSP. The Slow/Fast shear velocity (S/F) volume, computed from the outputs of the azimuthal AVOAz inversion, at the well location was compared to the WVSP interval HTI inversion results shown above. For this purpose a generalised Dix inversion (Gretchka *et al.*, 1999) was run on the MAZ WVSP result at key horizons. Figure 7 shows the S/F volume plot at the well location and the MAZ WVSP HTI interpretation. Significant changes in the inverted MAZ WVSP HTI azimuth correlate favourably with lower values found in the S/F volume for the Toolachee and Roseneath formations, where they match the sets of natural fractures derived from curvature attributes of surface seismic data in a near-bythe Nappamerri Trough (Abul Hair, *et el.*, 2012). In the Epsilon formation and the Murteree shale, the MAZ WVSP is reporting azimuthal variation similar to the hydraulic fracturing result at Encounter-1(Pitkin *et al.*, 2012). Also, when compared to the Munathiri 3D migrated CMP gather at well location, the bowing of the CMP gathers, sorted by offset and then by azimuth, changes when entering the Toolachee and Roseneath formations (black arrows)

In addition to the above-mentioned integration, synergy between MAZ WVSP and surface seismic processing was achieved in image validation, use of effective anisotropy processing parameters (eta parameter) and attenuation factor for surface seismic (Q) as well as validation of the de-multiple processes. The complete set of interactions between VSP and surface seismic data are summarised in Table 1 below.

Phase	From Surface Seismic to VSP	From VSP to Surface Seismic
Statics	One-way time total static solution provided for Walkaway VSP statics correction	Statics validation at well location.
Waveform Processing		Q- average estimation in analysis window
Velocity Analysis		Velocity profile at well location
Migration Velocity	Smooth 3D Velocity field for 3D migration	ETA function at well location
Demultiple		ISIMP de-multiple QC and processing input
Azimuthal AVO Inversion	HTI analysis validation	HTI analysis validation

Table 1. Points of contact between VSP and surface seismic

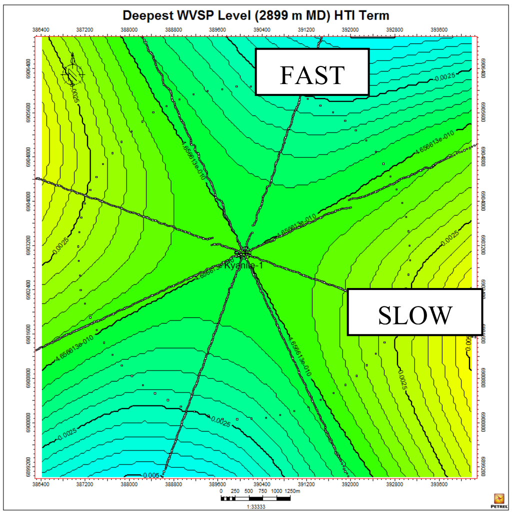

Figure 6. Example of HTI Inversion Colour represents travel time residuals: Blue – negative; Green – zero; Yellow - positive

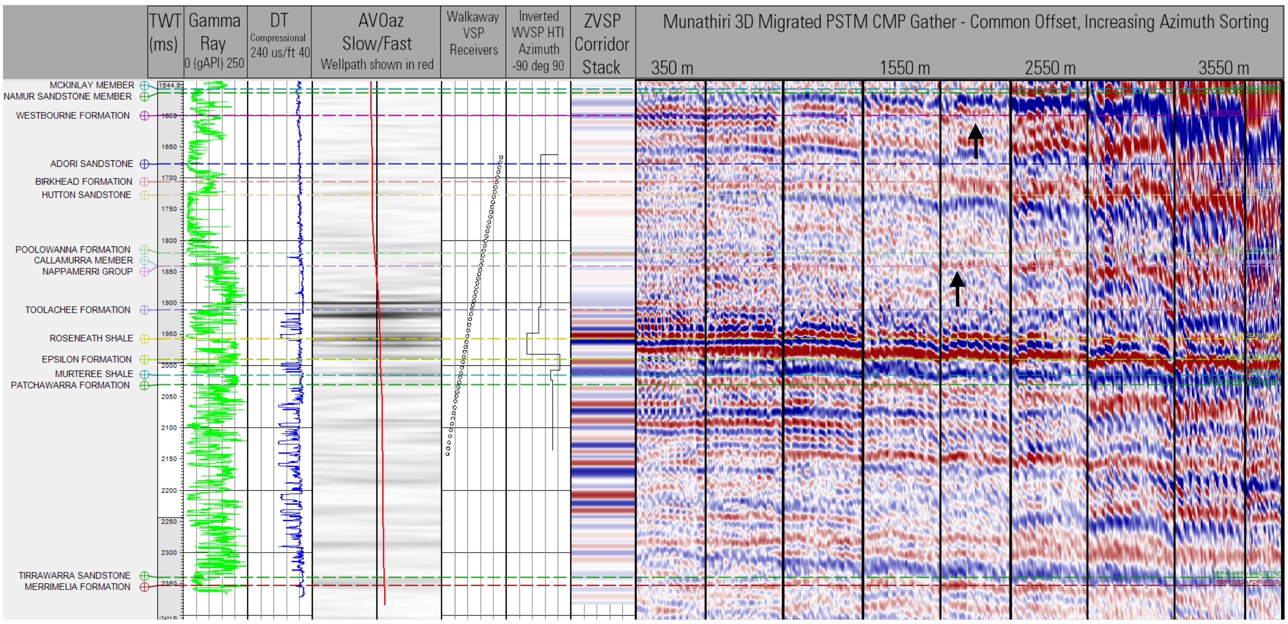

Figure 7: GR and DT logs, S/F shear velocity output of the AVOaz inversion showing the well in red (black indicates low S/F ratio; whilst white indicates S≈F velocity), MAZ WVSP tool settings and, MAZ WVSP HTI Interpretation and 3D CMP Gather at well location, showing the bowing due to azimuthal anisotropy

CONCLUSIONS

A comprehensive VSP survey acquired in Kyanite-1 has allowed validation of several processing steps associated with Munathiri 3D FAZ surface seismic volume. The ongoing work is now focusing on the effective de-multiple processing using the Inverse-scattering Internal Multiple Prediction (ISIMP) processing and subsequent azimuthal AVO inversion. These results will be calibrated by the WVSP imaging and the acquired Walkaround VSP. However, the major finding of this paper is the distinct VTI behaviour of the formations, indicating that the typical Anisotropic PreSTM processing stream may no longer be sufficient and that a PSDM approach should be favoured. Also, MAZ WVSP data have showed that the azimuthal variation component can be small in a gross RMS sense, but can be associated with the fracture and faulting networks of the shale/coal plays in an interval layer sense. Hence azimuthal AVO amplitude inversion is more likely to be the best analysis method for the Munathiri 3D dataset. The preparation of the surface seismic for this analysis will need to use well controlled trim statics and the azimuthal information to be preserved through imaging. The direct analysis of the azimuthal component of anisotropy through moveout velocity analysis requires further integration with

Walkaround VSP to form a conclusive answer, because the WVSP shows that the kinematic effect is weak in an RMS sense. This work is still ongoing and will form a basis of another study.

Integration between borehole seismic and surface seismic methods, such as input into the seismic velocity model and calibration of the initial AVOaz result is shown to provide a comprehensive solution for generation of a map of potential drilling targets. The integrated approach to surface and borehole seismic processing can be mutually beneficial to both methods. Moreover the results obtained from both approaches can be used to calibrate and validate each other and provide an overall better integrated and meaningful result.

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