Using Multiazimuth Seismic Data for Anisotropy Estimation in an Unconventional Reservoir

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SUMMARY

Productivity of a well in an unconventional reservoir is governed by various static and dynamic reservoir characteristics. Many of these characteristics have proxies among pre and post stack seismic attributes that can be derived from Multiazimuth 3D Seismic Data. The task of a geoscientist in this kind of reservoir is to understand these proxies to predict production behaviour. Natural fracture density and azimuth, as well as horizontal stress azimuth are the key attributes that seismic can help predict. Seismic Velocity and Amplitude variations with azimuth can be used to predict fracture strike, relative fracture density and define potential structural sweet spots. Azimuthal data from a Multiazimuth 3D seismic survey in the Nappamerri Trough of Cooper Basin has been interpreted to estimate fracture intensity and orientation. Co-rendered structural maps are used to create stress maps for different interval of interest. Stress maps help to identify areas of higher anisotropy and areas of lower minimum horizontal stress and so facilitate optimised well placement. To test the geological significance of these maps, correlation of stress vectors against well Image log and cross dipole sonic data was completed. This ground truth validates the prediction of direction and distribution of reservoir fractures based on full azimuth seismic data in this area.

Key words: Multiazimuth 3D; Anisotropy; Horizontal Stress; Stress maps

INTRODUCTION

The purpose of this study is to map anisotropy in an unconventional reservoir using Multiazimuth 3D seismic data. The area of interest for the study is the Gaschnitz 3D seismic survey in the Nappamerri Trough of the Cooper Basin, Australia (Figure 1a). The Cooper Basin is a north-east trending structural depression containing Late Carboniferous, Permian and Triassic fluvio-glacial, fluvio-deltaic and lacustrine deposits (Figure 1b). The Nappamerri Trough consists of overpressured (0.5 psi/ft. to 0.75 psi/ft.), gas saturated Permian section with little/no movable water. Tight sand, Deep Coal and Shale are three different unconventional plays in the Nappamerri Trough.

The primary reservoir units in this area are Toolachee, Daralingie, Epsilon, Patchawarra and Tirrawarra (Figure 1b). These reservoirs are low porosity (<8%) and low permeability. In low permeability reservoirs, production of oil and gas is often highly dependent on natural and/or induced fractures. The extent and azimuth of the induced fractures depend on the current day stress field.

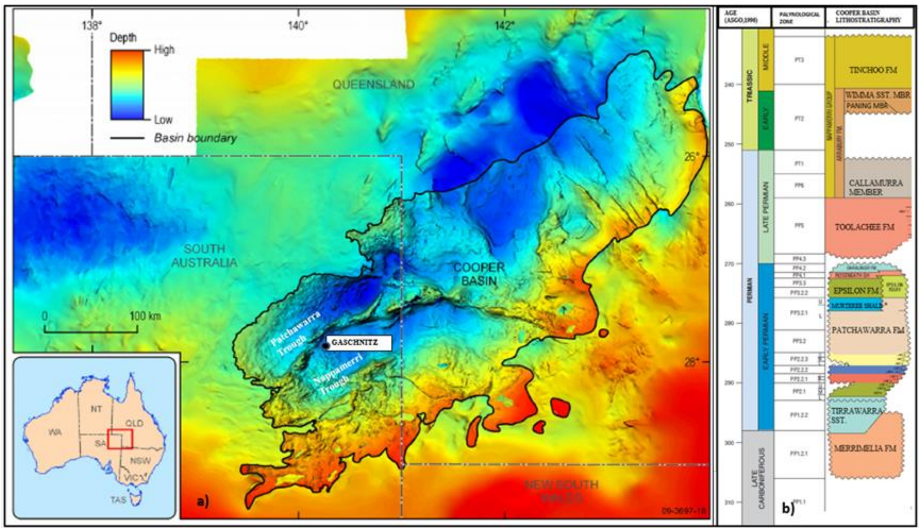

Figure 1: a) Study area Location map and Top Permian Horizon (Radke 2009)
b) A stratigraphic section illustrating Permian sequence in the Cooper Basin.

One of the keys for optimizing the development of such reservoirs lies in using seismic amplitude and velocity variation with azimuth to determine natural fracture strike and density and thus define production sweet spot trends. This piece of work is focussed around the tight sand play of Nappamerri Trough (Figure 2). The workflow for integrating structural and stress information to create stress maps is presented here.

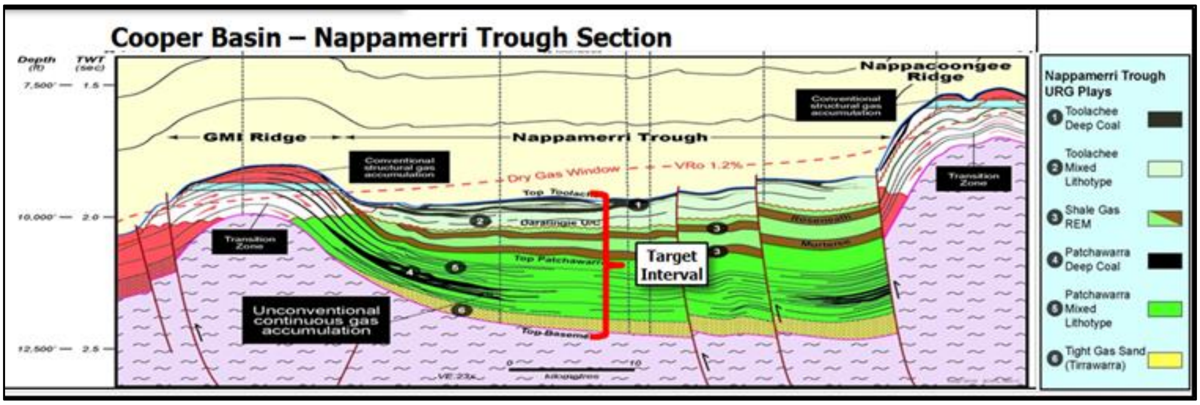

Figure 2: Key elements of Nappamerri Trough Unconventional Play

The Gaschnitz 3D seismic survey is a 120 square km Multiazimuth Survey recorded with 6km offset and 2ms sampling interval. The receiver and source station interval was 50 m. Receiver and source lines were spaced 400 m apart. Total length of lines was 638.80 km.

This long offset, full azimuth data was processed to derive both a high quality image and to extract the azimuthal anisotropy information sampled by this type of data acquisition. The fracture detection technology of wide azimuth 3D seismic data is based on amplitude and velocity information of different offset and azimuth. The original data acquisition is designed to record high folds and high Signal to noise (S/N) ratio. When measured, the anisotropy can yield important reservoir parameters related to fractures and the stress field.

Seismic Anisotropy

Anisotropy is defined as the 'variation of a physical property depending on the direction in which it is measured' (Sheriff, 2002). Seismic wave propagation in an anisotropic heterogeneous media can be simplified into two types of anisotropy:

1) Vertical Transverse Isotropy (VTI) with a vertical axis of symmetry. This is associated with layering and shale, and is found where gravity is the dominant factor.
2) Horizontal Transverse Isotropy (HTI) with a horizontal axis of symmetry. This is associated with cracks and fractures, and is found where horizontal stress is the dominant factor. This is also called azimuthal anisotropy.

This study is focussing on Horizontal Transverse Isotropy.

Subsurface fractures occur in sets and are locally aligned in one dominant direction. The P-waves are affected when their propagation path (source-receiver azimuth) is perpendicular to the vertical aligned fractures. Fractures act as speed bumps- they can slow seismic waves travelling perpendicular to them, while waves travelling parallel to them are not really affected. The goal is to work backwards to estimate physical properties of interest such as fracture intensity and orientation i.e. where the speed bumps are and which way they are oriented (Figure 3).

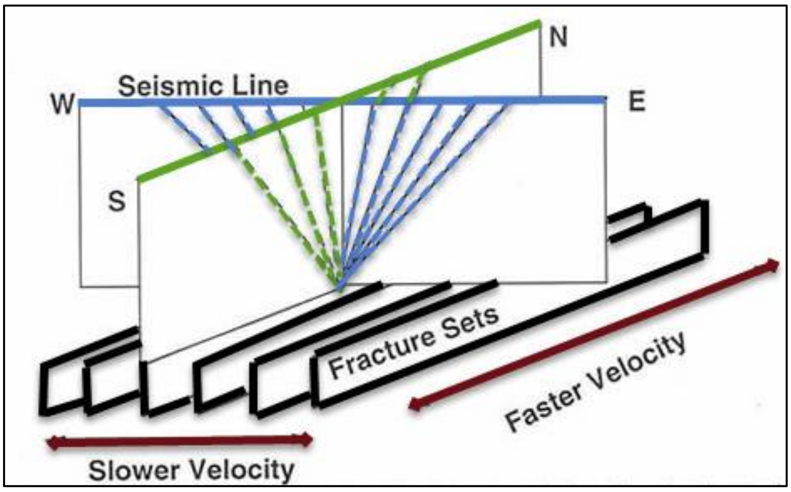

Figure 3: Schematic representation of variation in Seismic velocity with azimuth caused by aligned fracture sets.

METHOD AND RESULTS

Two key azimuthal fracture detection techniques using 3D seismic data are: P wave azimuthal AVO analysis (AVAZ) and P wave azimuthal Velocity analysis (VVAZ). The AVAZ technique is based on the work of Ruger (1998) and the VVAZ technique is based on the Zheng inversion (Zheng, 2006). This work demonstrates the application of VVAZ technique. Grechka and Tsvankin (1998, 1999) defined azimuthal-dependent NMO velocity by a 3D ellipse. Ellipse model is a simple model, characterized by major axis Vfast, the minor axis Vslow and the azimuthal orientation of Vfast (Figure 4). The ratio of these two velocities provides an estimate of the magnitude of anisotropy.

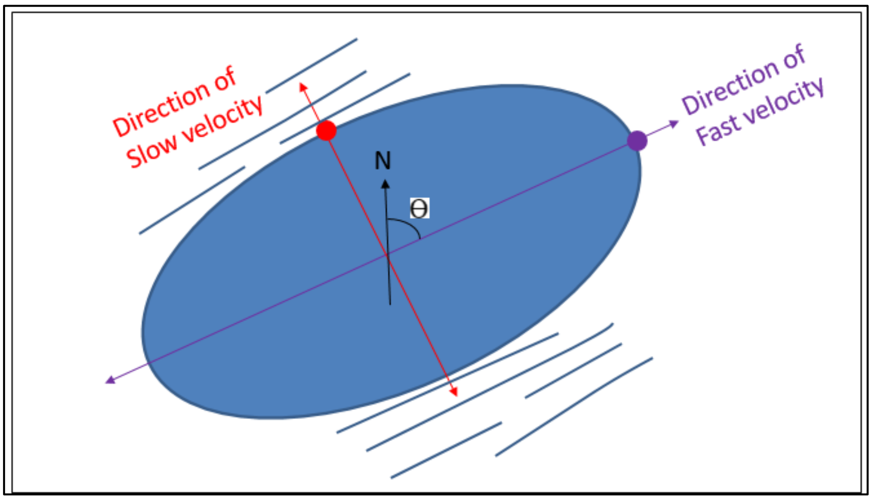

Figure 4: Simple Velocity Ellipse Model

Anisotropy analysis is conducted using interval velocity. This interval velocity is sensitive to lithology, porosity, pore fill and minimum horizontal stress. The fast direction of the P- interval velocity is interpreted as parallel to the open fracture network and the maximum horizontal stress.

Multiazimuth Seismic Data Analysis

The most difficult task in multiazimuth seismic interpretation is analysing the huge increase in data when compared to traditional seismic acquisition and interpretation. Therefore, it is important to understand different sets of processing deliverables and the information they carry.

In case anisotropy exists in the overburden layers, then the azimuthal variation in the stacking velocity and the amplitude will have the overburden anisotropy interference. In order to minimise the overburden anisotropy effect, a limited time window for anisotropy analysis was selected to cover only the fractured layer Anisotropy analysis was conducted utilizing layered interval velocity and a 15-20 ms window of RMS Amplitude. Interval velocities are from Dix calculation.

Multiazimuth seismic interpretation using VAVZ technique, begins with mapping of seismic reflectors and faults throughout the survey area to create detailed time structure maps. The primary seismic volume for this structural interpretation was a dip steered full azimuth volume. For fault interpretation additional seismic attribute volumes such as similarity and curvature were extracted from the dip steered cube. These extracted attributes were analysed and used to guide the fault interpretation. The similarity data provided a better response to faults (Figure 5).

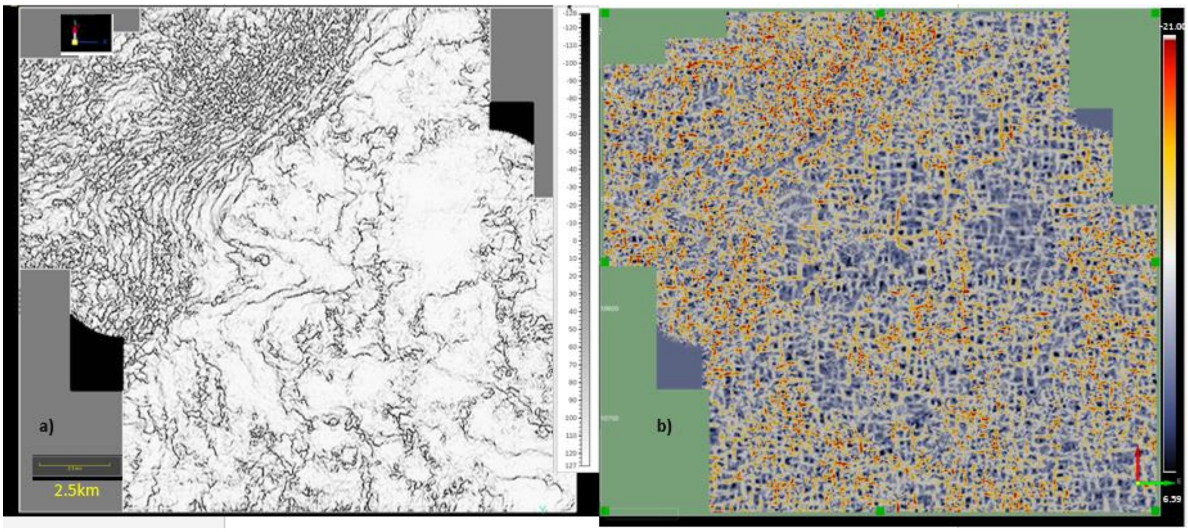

Figure 5: a) Similarity slice b) Curvature slice

After time structure maps for horizons of interest are constructed, then the 3D stacking velocity cubes are sliced at the horizon time and the stacking velocity extracted for the horizons of interest. From these maps, the Dix interval velocity for intervals of interest can be calculated. The key seismic volumes of interest are- VTI HTI Prestack Time migrated Volume, Horizon based Interval HTI Vslow velocity, Horizon based Interval HTI Vfast azimuth and Horizon based Interval HTI Vfast magnitude. Attribute slices for the reflector of interest are constructed from these different volumes (Figure 6) .The most useful and practical technique in Multiazimuth seismic interpretation is to put all these relevant information on one map.

A key learning from this study was to incorporate multiple attributes in one map to understand the density and orientation of fracture network.

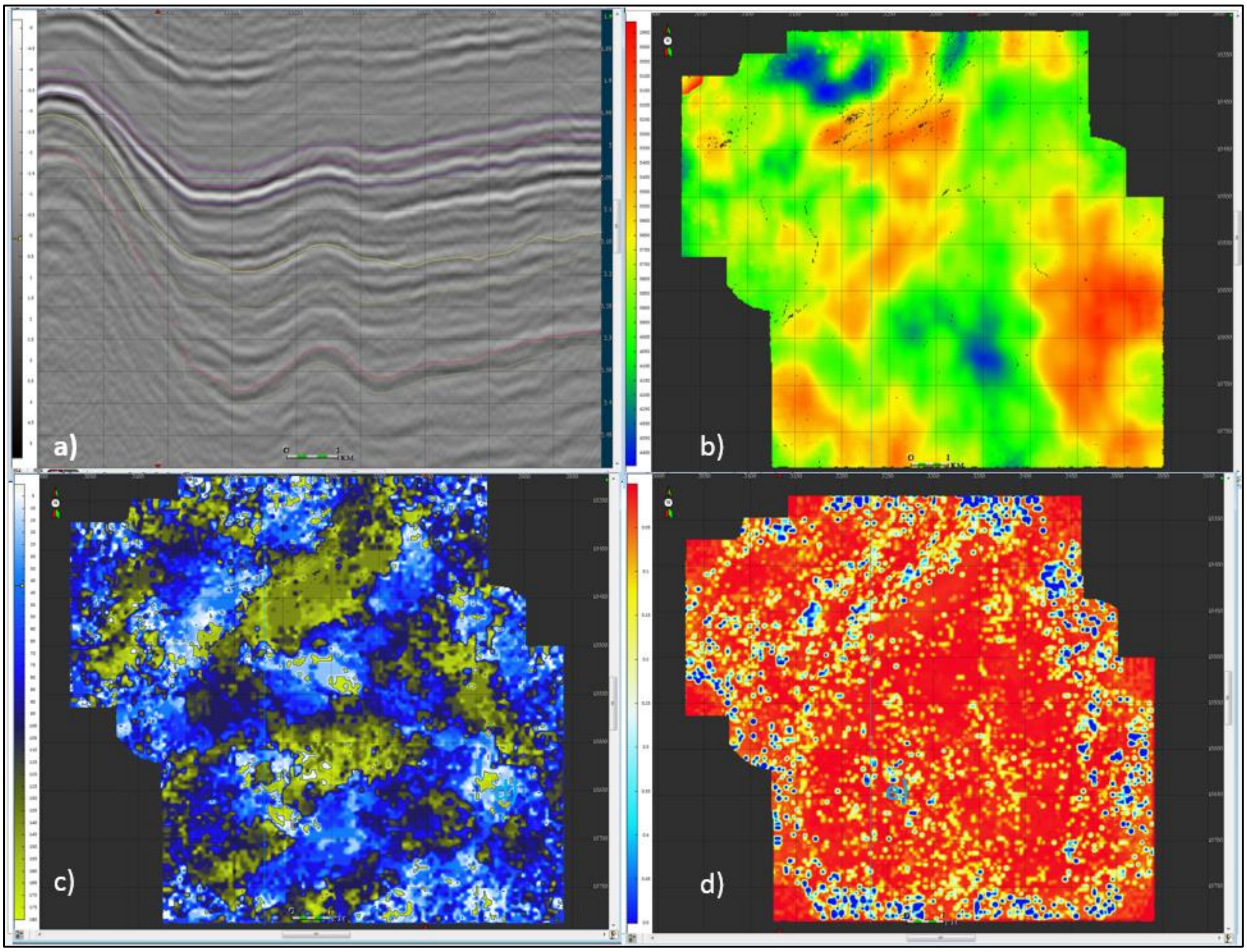

Figure 6: a) Prestack Time Migrated volume b) Interval HTI Vslow Velocity slice c) Magnitude of Anisotropy slice d) Interval HTI Vfast azimuth slice

Co-rendering and Creating Stress maps

The four principal elements used to create the stress maps are - Structure contours, Slow Interval Velocity ($V_{intslow}$) for background colour, Azimuth of Fast interval velocity & magnitude of anisotropy.

Here the magnitude of anisotropy is defined as ($V_{intfast}$-$V_{intslow}$/$V_{intfast}$). For building the stress map, it is necessary to generate a vector that comprises of: a length (magnitude of anisotropy) and an azimuth ($V_{int\ fast}$ direction or the bright amplitude direction). I have used two separate grid files to create these vectors: one grid consists of length information (Figure 6b) and the other grid contains angle information (Figure 6c). Co-rendering of structure map, Interval HTI Vslow map and vector map was completed using Golden Software Surfer. This step was repeated for all the target intervals. The results shown here are for Toolachee reservoir only.

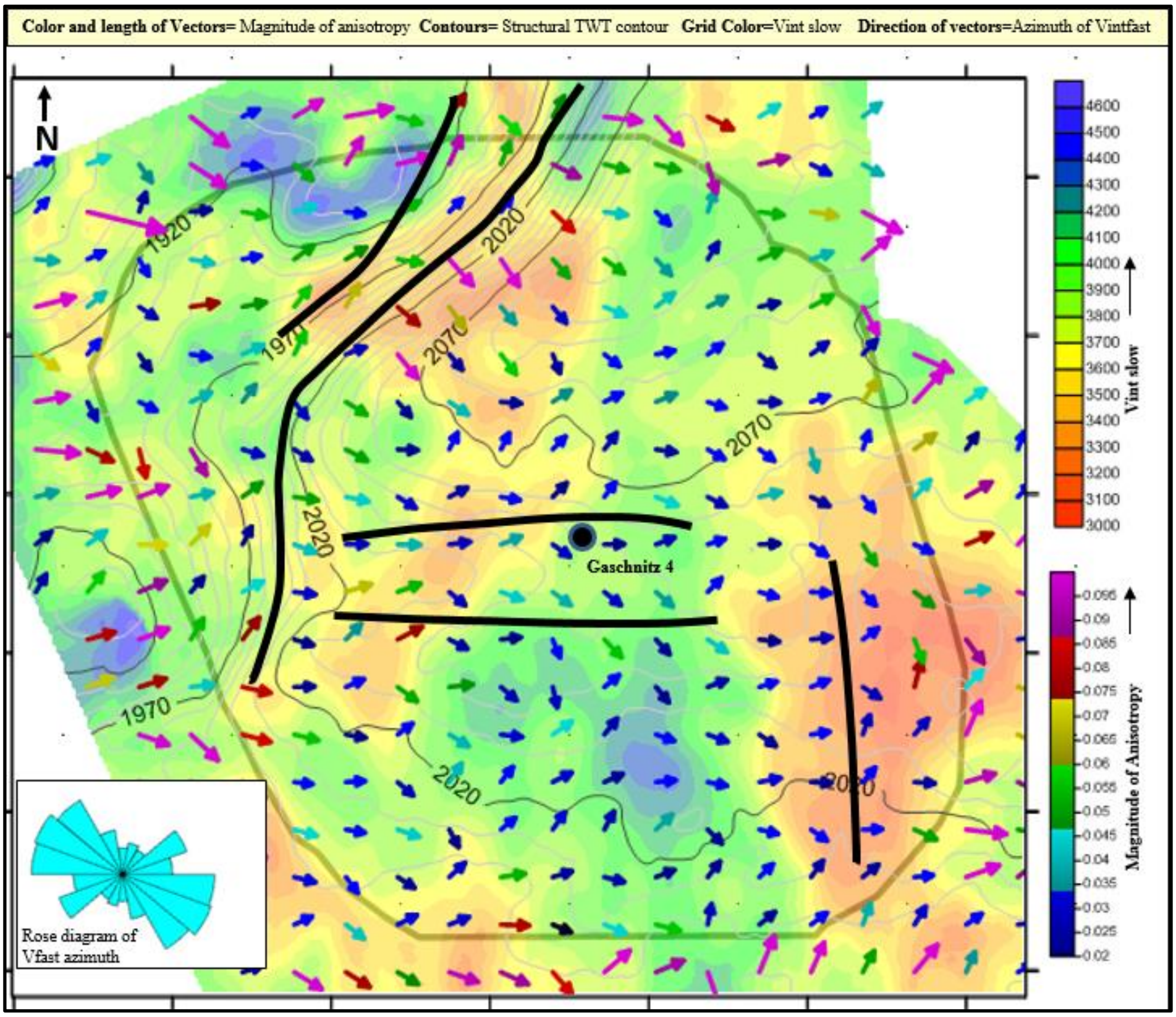

Figure 7: Co-rendered stress map showing faults, outline of high fold area, location of Gaschnitz 4 and the Rose diagram for Vint fast azimuth

The length of the stress vector is directly proportional to the magnitude of anisotropy and the color of the vector shows the absolute magnitude of anisotropy. The longer vectors at the survey edge are the artefacts due to poor signal to noise ratio. Care must be taken that variations in acquisition, processing, or interpretation do not masquerade as azimuthal anisotropy. The direction of the stress vector is the azimuth of Vint fast. The background color of the stress map is the Vint slow. Low Vint slow indicates areas of low minimum horizontal stress

The resultant azimuth of our Vint fast shows many local variations of the stress field near the faulted areas (Figure 7). This shows random azimuths and longer vectors near the main SE- NW fault. However, the dominant direction based on the statistics is WNW-ESE (see Rose diagram in Figure 7).

The anisotropy from amplitude-based maps has also been generated, but unfortunately, seismic amplitude is a very sensitive attribute. Presence of a small amount of noise significantly distorts the results. Therefore amplitude is not considered a reliable way to measure anisotropy in this area.

A stress map identifies areas of higher anisotropy (long vectors), areas of low minimum horizontal stress (low Vint slow). Breakdown pressure is low for regions of low minimum horizontal stress. This is important to understand areas to frac based on low instantaneous pressure gradients and optimise frac design.

It is important to validate these stress maps with the well data. Here the stress maps based on the 3D seismic analysis are compared to Borehole Breakout interpreted from Image Logs and Cross Dipole Sonic.

Image Log Analysis

Image log data from Gaschnitz 4 has been used for validation. STAR borehole image log data was run in Gaschnitz 4 by Baker Hughes. The structural and sedimentological interpretation of this STAR borehole image log data was completed by Task Fronterra Geoscience.

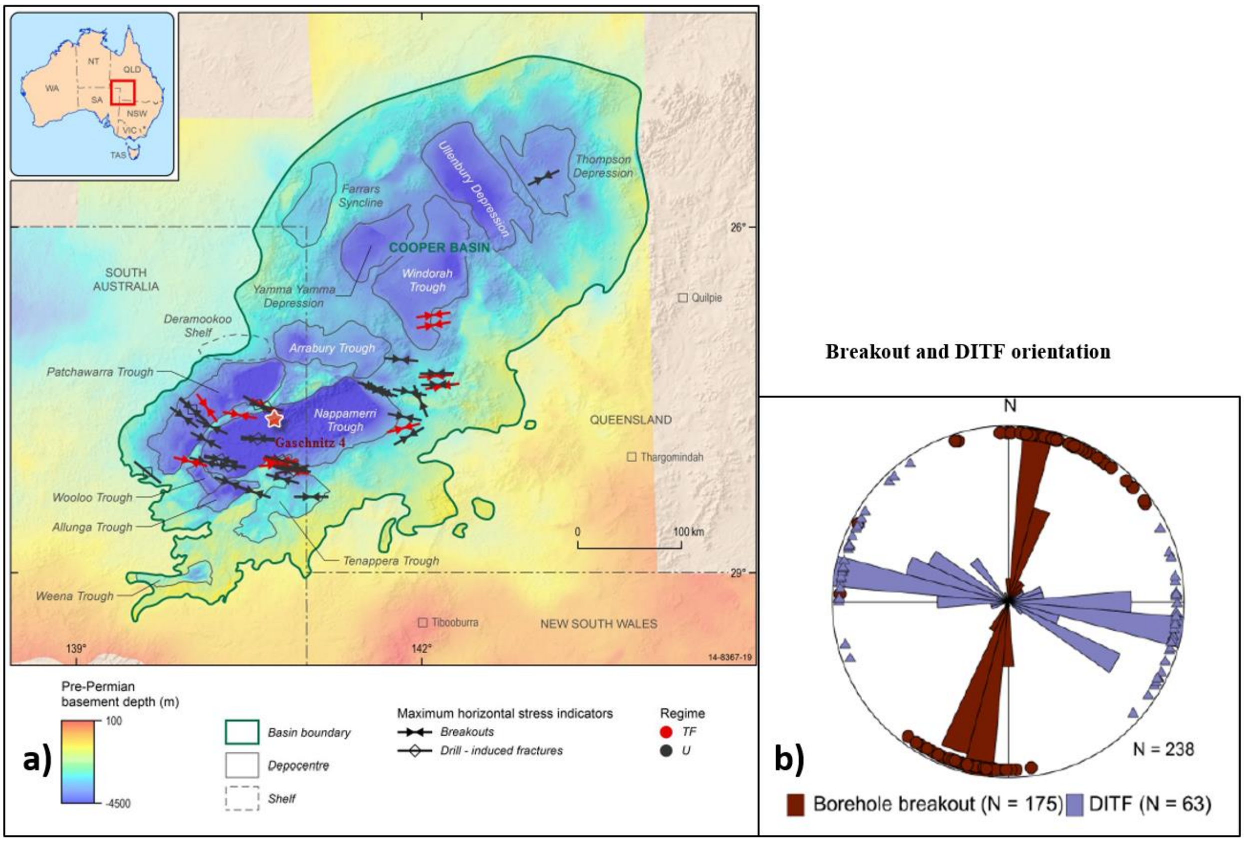

Figure8: a) Maximum horizontal stress indicators (Reynolds et al., 2005, Hill et al., 2008) and regional stress trajectories (Hills and Reynolds, 2000) overlain on depth to base Cooper Basin.
b) Breakout and DITF orientation for Gaschnitz 4

Maximum present day horizontal stress orientations across the Cooper Basin have been established from borehole breakouts and drilling induced fractures (Hills and Reynolds 2003; Reynolds et al., 2005, Hills et al., 2008). These studies observe an east-west maximum horizontal stress orientation that is consistent over much of the basin, except in the Patchawarra Trough, where maximum horizontal stress rotates to a northwest-south east orientation (Figure 8a).

Gaschnitz -4 borehole is nearly vertical throughout the study interval. Image log interpretation identified a total of 175 borehole breakouts and 63 drilling induced tensile fractures in the Gaschnitz-4 STAR image. Breakouts were mainly evident in sandstone intervals throughout the well and show a preferential NNE-SSW orientation.

Drilling induced tensile fractures (DITF) are present in argillaceous intervals in the well. DITF show a strong preferred ESE-WNW orientation, which is perpendicular to the observed breakout orientation.

Together breakout and DITF indicate a NNE-SSW minimum in-situ stress (S_{hmin}) orientation and an ESE-WNW maximum in-situ stress (S_{Hmax}) orientation (Figure 8b). In-situ stress determined from the borehole breakout and DITF data in Gaschnitz-4 are reasonably consistent with local trends determined from the world stress map and the overall E-W regional stress for the Cooper Basin. Stress maps from seismic azimuthal analysis also show vectors oriented ESE-WNW near Gaschnitz 4 well (Figure 7). This is a good validation of the stress vectors from multi- azimuthal 3D seismic analysis.

Cross Multipole Array Acoustic Log (XMAC) Azimuthal Anisotropy Analysis

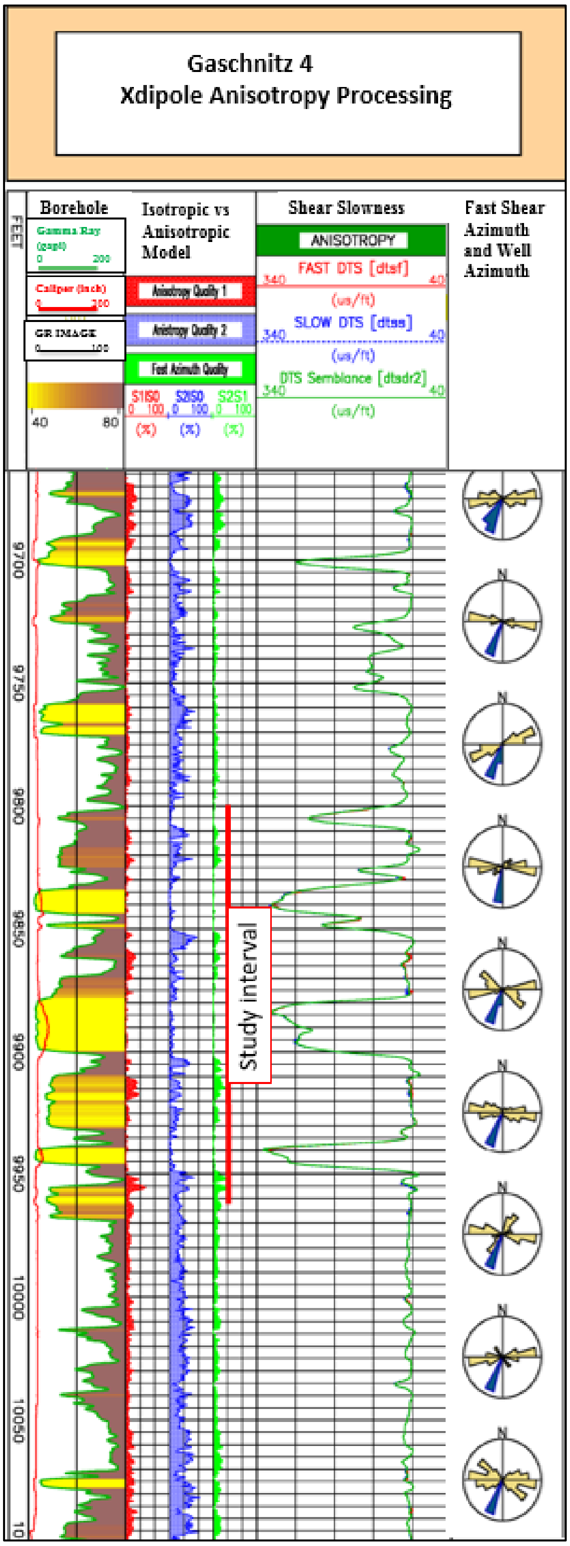

Figure 9: Cross Dipole Anisotropy Processing

In Gaschnitz 4, a Cross Dipole Sonic log was acquired and processed by Baker Hughes.

Anisotropy processing shows that the preferred orientation of the fast shear azimuth for the Toolachee reservoir section is NW-SE (Figure 9). The orientation of fast shear azimuth matches the known stress field orientation for the Cooper Basin. These data are in alignment with the vector azimuth generated by stress maps from multi-azimuthal 3D seismic analysis.

CONCLUSIONS

In unconventional reservoirs, fractures and azimuth variation of the horizontal stress cause azimuthal anisotropy. Seismic P-waves travelling through fractured media exhibit azimuthal variation in travel time and amplitude. If these signatures are measured and interpreted, valuable information related to either fractures presence or orientation and/or the stress field can be inferred. Understanding the fracture intensity, direction and maximum stress field is helpful in the choice of drilling direction, fracture placement, well design and cost effective completion.

More recently, high quality wide azimuth seismic surveys are being acquired to enhance the total value of unconventional assets through improved imaging quality, resolution and new deliverables including representations of fracture or stress orientations and intensity. However multiazimuth seismic interpretation is still a challenging issue. There are different opinions regarding the efficacy of VVAZ/AVAZ techniques. In Gaschnitz, VVAZ technique was practically more effective for creating stress maps. This study shows a novel way for interpreters to interact with seismic data to create stress maps. It is observed that the seismic anisotropy maps showed a dominant direction (WNW-ESE) that matches with the well data and validates horizontal stress direction. However we need more well-bore data to provide a better statistical validation. In the production stage of the field, it is recommended to test and validate these stress maps with dynamic reservoir data.

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