Azimuthal Shear Wave Anisotropy Studies In The North-West Shelf Of Australia

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***Abstract*—Significant stress induced azimuthal anisotropy was previously reported for Australian North West Shelf, the benefits of azimuthal shear wave anisotropy studies in fracture orientation, stress field investigations and enhancement of seismic imaging with the availability of large volumes of well data in public domain to study anisotropy in the North West Shelf has prompted this research. Zero-offset VSP data from 9 (nine) wells in the North-West Shelf of Australia were analysed for the presence of azimuthal shear wave anisotropy using shear wave splitting phenomenon. Results obtained showed the presence of azimuthal shear wave anisotropy in 3(three) wells namely Glencoe 1, Lambert 9 and Satyr 1, whereas, 6 (six) wells showed no presence of azimuthal shear wave anisotropy namely Omar 1, Theo 1, Thebe 2, Torosa 2, Noblige 1 and Wheatstone 4. Velocities obtained from the analysis of Zero-offset VSP data were compared to dipole sonic image data for the wells where dipole sonic image data was available. Results from the comparison showed very good agreement for both datasets and validated the accuracy of the method. The results from the analysis also showed fast shear waves in wells with anisotropy had an azimuth of 150 to 160 ° which coincided with the principal maximum horizontal stress direction in the North-West Shelf. Observations also showed that orientation of data using P wave polarisation was unstable, hence, tools with orientation sensors would be required to obtain reliable estimates of fast and slow shear wave polarisation azimuths.**

Keywords—Azimuth, Anisotropy, shear wave, dipole sonic, North West shelf, Australia.

INTRODUCTION

The North-West Shelf of Australia has been a hotbed for hydrocarbon exploration activities for over half a century. About 2500 wells have been drilled in the area most having VSP and Cross dipole sonic data. Since the inception of exploratory activities in the North-West Shelf, geophysical procedures have extensively been employed to better understand the sub-surface structure in order to reduce drilling costs. To achieve proper imaging of the sub-surface using seismic, it is important to take into consideration factors affecting seismic velocities in the sub-surface which includes anisotropy. [1] defined anisotropy as a change of property with direction when measured from the same location and inhomogeneity as a change in properties when measured from the same direction. Shear wave propagation cause particles to be polarised vectorially in 3 dimensions, with each component of the polarised wave train containing significant information about the structure of the geologic material through which the wave travels. Characterisation of fractures, their orientation and stress field investigations was determined by shear wave analysis [2]. Comparison of the direction of maximum horizontal stress from tiltmeter data analysis and polarisation of faster component of shear wave from a nine component VSP data by [3] in the Lost Hills Field of California, showed some agreeable alignment. Investigating the relationship between orientation of fractures and azimuthal anisotropy in the Austin Chalk, Texas [4], he employed multi-component shear wave VSP data. His investigation showed agreement in the significant velocity contrast observed in S-wave polarised parallel and perpendicular to the fracture orientation observed on image logs from borehole televiewer. The importance of azimuthal shear wave anisotropy as a tool for fracture and stress field characterisation was emphasized in [5], a new approach in estimating the variation in fast and slow shear wave velocities and the orientation of polarisation planes using ZVSP data to study shear wave anisotropy in the North-West Shelf Australia was investigated. The method presented showed good comparison of anisotropy estimates obtained from VSP data and that from Cross-dipole sonic log data in both marine environment and varying source types in land investigations.

Previously, there had been reports of significant stress induced azimuthal anisotropy in the North-West Shelf of Australia [6]; [5]; [7]. This had resulted in great challenges in seismic imaging and modelling. In order to effectively image the subsurface, one requires a good knowledge of the velocities at which seismic waves are propagated both horizontally and vertically in the subsurface. The velocities at which waves are propagated are dependent on the degree of anisotropy, amongst other factors, along the ray path. This research investigates the presence of azimuthal shear wave anisotropy in the North-West Shelf of Australia and its regional distribution.

REGIONAL GEOLOGY AND STRESS FIELDS

Wells selected for analysis were located in the North Carnarvon (Satyr1, Glencoe1, Lambert9, Thebe2, Theo1, Wheatstone4 and Noblige1) and Browse Basins (Omar1 and Torosa2) of the North-West Shelf (fig. 1). The Carnarvon Basin covers an estimated area of about 650,000 sq. km. 17% exists onshore, while an extensive 83% continues offshore to the Continental and Oceanic plate boundary. The Basin extends along the Western and North-Western coastline of Western Australia from Geraldton to Karratha [8]. A set of sub-basins containing predominantly Palaeozoic sediments of up to 7 km are defined by generally North-Wards trending structures. Trending North-East above the Palaeozoic sediments exists Sub-basins containing Mesozoic and Cainozoic sequences which have a maximum thickness of up to 15 km. The “Palaeozoic Sub-basins” as the Southern set of Sub-basins are usually called comprise of the Bidgemia, Byro, Gascoyne and Merlinleigh Sub-basins [9]. The “Mesozoic Sub-basins” as the Northern set of Sub-basins are known as comprises the Dampler, Exmouth, Investigator and Barrow Sub-basins, also the Rankin Platform and Kangaroo syncline. The outer parts are defined by a southwards thinning wedge of Mesozoic sedimentary rocks, resting above either the Pre-Cambrian Lambert Shelf or the Palaeozoic Peedamullah Shelf. Above the basement, to the west of the Gascoyne Sub-Basin is a thin cover of Mesozoic sedimentary rocks known as the Bernier Platform.

Tectonic events led to the breaking up of the Gondwana, forming a passive margin basin known as the Browse Basin. It is located off North-Western Australia in a NE – SW offshore direction. The Browse basin is a sedimentary basin underlying about 105,000 sq. km of the continental shelf and slope [10]. In the centre of the Browse Basin exists up to 11 km of Permo-Carboniferous to Quaternary sediments in [10]. To the east, the boundary basin is defined by the Kimberly Block. Much thinner sediment sequences exist in the Leveque Shelf, Yampi Shelf and the Prudhoe Terrace which are central parts of the Browse Basin. The Ashmore platform defines the Northern boundary of the basin and the Western boundary is defined by Scott Plateau. The Southern part of the Basin adjacent to the Canning Basin is poorly defined [10].

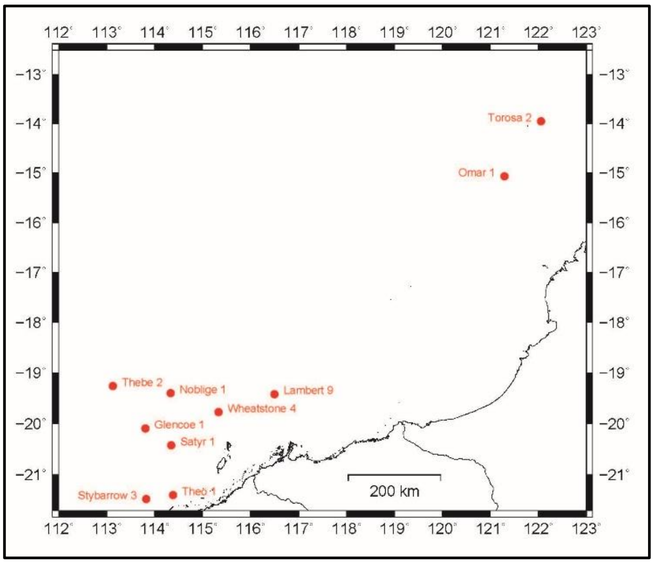

Fig. 1Location of wells on the North West Shelf of Australia selected for analysis

METHODOLOGY

Large volume of well data is available for Western Australia in Public domain, selected data having both zero-offset VSP and cross dipole shear sonic data was employed for work. A detailed workflow of pre-processing and anisotropy analysis is shown in [11]. High quality data from the North-West shelf was selected with ZVSP data having a maximum deviation of 5° acquired from 2007 to date. Quality of shear component data and availability of cross dipole shear sonic data was also taken into consideration.

Table 1VSP and cross-dipole sonic data availability

WELLS	VSP (depth in meters)	Dipole Sonic (depth in meters)
Glencoe1	2200 - 3400	1234 - 4499
Lambert9	1505 - 3205	1976 - 3233
Omar1	2000 - 5060	-
Thebe2	1600 - 2486	1738 - 2498
Theo1	878 - 1638	-
Torosa2	3002 - 4282	3335 - 4796
Wheatsone4	2010 - 3510	2975 - 3554
Noblige1	1900 - 4420	2679 - 4549
Satyr1	3000 - 4560	3203 - 4566

Result of tool orientation: The angle between the vertical axis of the tool and the polarisation of the P-wave was computed at all depths of the well (fig. 9), the blue line represented the estimated angle while the black dots on the figure represented the actual computed angle. Depths at which the computed (black dots) fell close to the estimated (blue dotted line) showed the tool worked well, whereas, where the computed fell far from the estimated showed tool malfunction.

Patterns observed in tool rotation were grouped in to three major categories. The results in the first group showed that the horizontal component of the tool rotated freely at all depths(fig. 2a), also the estimated and computed angle between vertical axis of tool and polarisation of p-wave showed good agreement which implied that the tool worked well, this was seen in Glencoe 1, Theo 1, Wheatstone 4 and Noblige 1 wells. The second group of wells showed preferred rotation of the tool at some depth interval and free rotation at other depths. The computed and estimated angle between the vertical axis of the tool and P-wave polarisation showed the tool worked well to a depth of about 3000 m after which it began to malfunction (figure2b), as observed in Torosa 2, Omar 1 and Satyr 1 wells. The third group of wells showed a preferred rotation of the tool at all depth intervals of the well, the computed and estimated angle did not show very good agreement, which implied the tool malfunctioned at all depths (fig. 2c), this was observed in Lambert 9 and Thebe 2 wells.

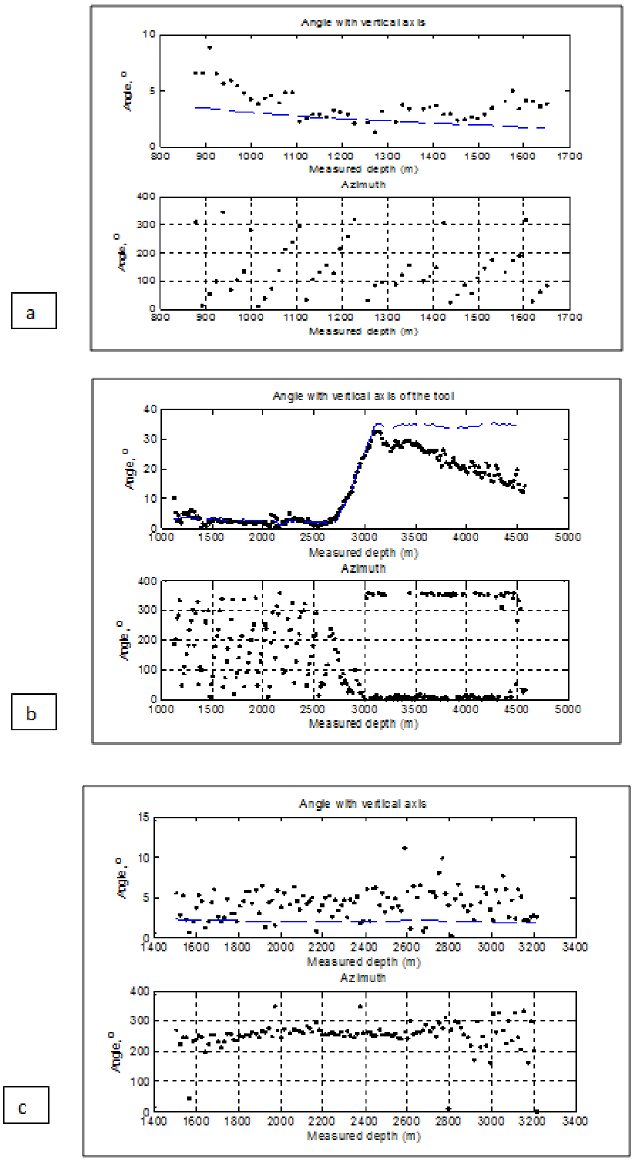

Fig. 2Orientation of tool (a) tool worked very well (b) tool worked well at certain depth intervals (c) tool worked poorly at all depths

Parameters for analysis: The velocity spectrum analysis for the wells were done over an azimuth of 0 – 180˚ for all the wells with a azimuth step of 2.5˚, a depth step of 20 m was also used for all wells with a 0.005 km/s step velocity (Table 2). The depth interval was for the analysis was varied to accommodate the whole depth range of the input data, time-gate for the analysis was chosen to accommodate the first arrival and shear events. The depth window varied the resolution in velocity which reduced interference from other waves present, a higher depth window, thus, implied a higher resolution in velocity. The velocity range was chosen to accommodate the maximum and minimum shear wave velocities observed on the seismic sections.

TABLE 2Parameters use for azimuthal velocity spectrum analysis

Borehole	depth interval(m)	Time gate (ms)	Depth window(m)	Velocity range(km/s)
Glencoe1	2200 – 4500	400 – 5000	70	1.0 – 3.2
Lambert9	1505 – 3205	400 – 5000	100	1.1 – 3.2
Omar1	2000 – 5200	400 – 3000	70	0.5 – 3.0
Theo1	878 – 1638	400 – 4000	70	0.5 – 2.3
Thebe2	1606 – 2486	500 – 3000	55	0.6 – 1.6
Torosa2	3002 – 4282	400 – 3000	60	1.0 – 3.0
Wheatstone4	2010 – 3510	400 – 4000	150	0.7 – 2.5
Noblige1	1900 – 4420	400 – 5000	100	0.6 – 3.2
Satyr1	3000 – 4570	500 – 4000	150	1.2 – 3.2

RESULTS AND INTERPRETATION

Results of analysis obtained showed presence of anisotropy in two wells, whereas, seven wells showed no sign of the presence of anisotropy at all depths.

WELLS WITH ANISOTROPY

Results from velocity spectrum analysis on Lambert 9 showed fast and slow apparent shear wave velocity extremas at a depth of 3,005 m (fig. 3). Fast shear wave of 2.1 km/s was observed at an azimuth of 120º and the slow shear wave of 2.0 km/s was observed at an azimuth of 30º. In order to verify the accuracy of the velocities obtained by the analysis, apparent velocities from the analysis was plotted with smoothed cross dipole sonic data. Results showed very good agreement (fig. 4). Satyr 1 also showed presence of anisotropy at a depth of 3,200 m (fig.5), with a fast shear wave of 2.05 km/s observed at an azimuth of 150º and slow shear wave velocity of 1.9 km/s at an azimuth of 60º. Plot of smoothed cross dipole sonic and velocities from analysis carried out showed reasonable agreement (fig. 6). The velocities from smoothed cross dipole sonic data on Satyr showed velocities were quite erratic over a velocity range of 2.0 km/s to 2.3 km/s increasing slightly with depth, even with this randomness the velocities obtained from the analysis still fell within the range also increasing with depth. This implies the analysis had a very high level of accuracy.

LAMBERT 9

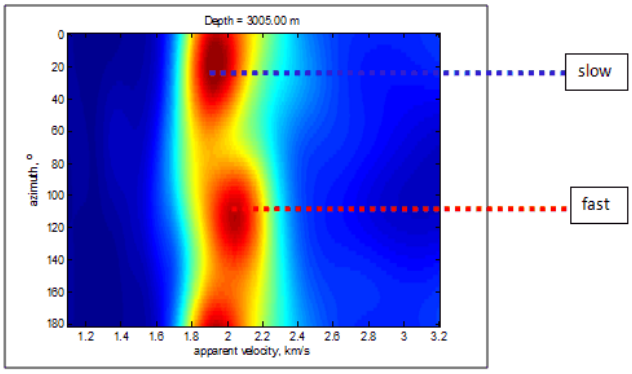

Fig. 3Velocity spectrum at depth 3005 m showing the presence of anisotropy

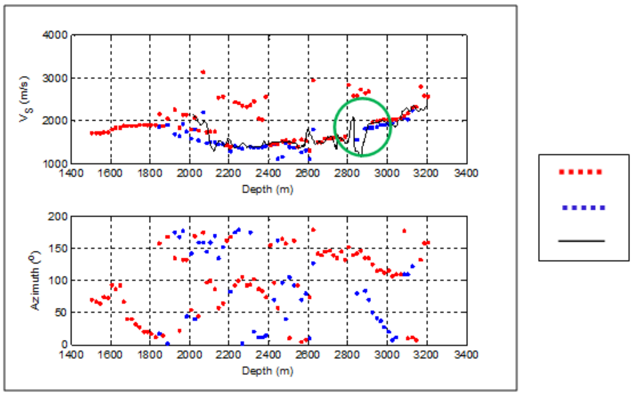

Fig. 4Picked velocities from velocity spectrum plotted with smoothed Dipole sonic data through the well showing fast and slow shear waves at 3,005 m

SATYR 1

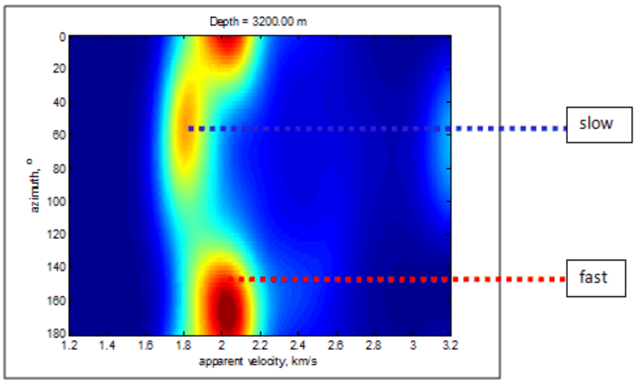

Fig. 5Velocity spectrum at depth 3200 m showing presence of anisotropy

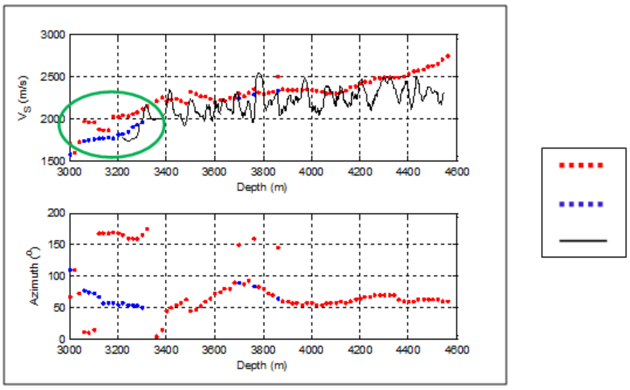

Fig. 6Picked velocities from velocity spectrum plotted with smoothed Dipole sonic data through the well showing fast and slow shear waves at 3200 m

WELLS WITHOUT ANISOTROPY

Wells Glencoe 1, Omar 1, Theo 1, Thebe 2, Torosa 2, Noblige 1 and Wheatstone 4 showed no signs of anisotropy. Results of velocity spectrum analysis on these wells were characterised by a single apparent shear velocity extreme at all depths, which implied an absence of anisotropy (fig. 7). Cross dipole sonic data was plotted with the velocities obtained from velocity analysis on all wells with cross dipole data. The results showed velocities were reasonably accurate in all cases validating the analysis method (fig. 8).

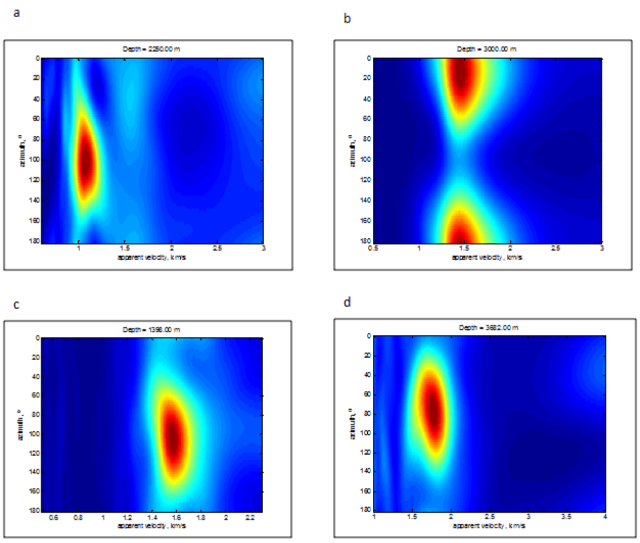

Fig. 7Results of velocity analysis showing no anisotropy (a) Glencoe1 at 2250 m (b) Omar1 at 3000 m (c) Theo1 at 1398 m (d) Torosa2 at 3682 m

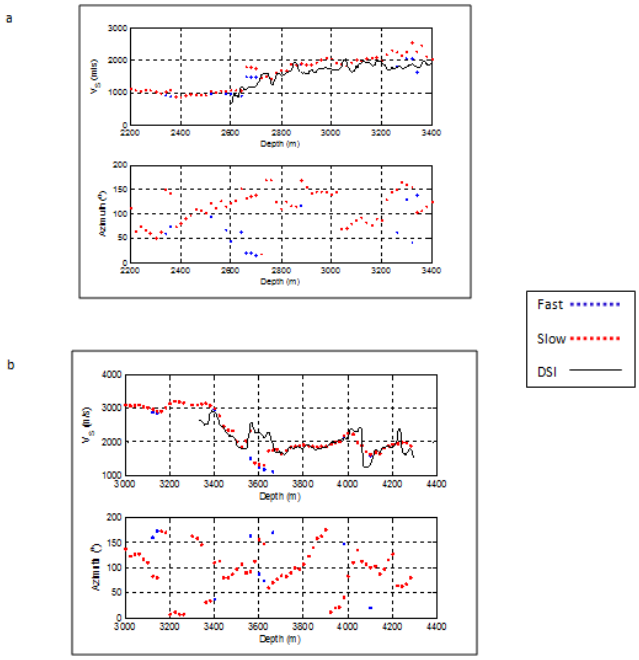

Fig. 8 Picked velocities from velocity spectrum plotted with smoothed Dipole sonic data through the well showing no anisotropy (a) Glencoe1 (b) Torosa2

SUMMARY AND CONCLUSION

Nine wells was analysed for the presence of azimuthal shear wave anisotropy in the North-West Shelf of Australia using VSP data. Apparent velocities obtained by the analysis of VSP data were compared to dipole sonic image data for the wells to determine the accuracy of the method. Results showed the presence of azimuthal shear wave anisotropy in Lambert 9 and Satyr 1, whereas, no azimuthal shear wave anisotropy was observed in Glencoe 1, Omar 1, Theo 1, Thebe 2, Torosa 2, Noblige 1 and Wheatstone 4.

Results obtained for Lambert 9 also showed the presence of azimuthal shear wave anisotropy at a depth of 3000 m, fast shear waves of about 2 km/s was observed to have an azimuth of 120˚, whereas, slow shear waves of about 1.9 km/s were observed at 30˚. Very reasonable agreement was observed between the dipole sonic log and apparent velocities from VSP analysis. Satyr 1 clearly showed the presence of azimuthal shear wave anisotropy at 3200 m with the fast apparent shear velocity of 2 km/s observed at 150˚ and slow apparent velocity of about 1.9 km/s at about 60˚.

Dipole sonic image data from all wells without anisotropy, except Omar 1 and Theo 1 which had no dipole sonic data, showed very good agreement with apparent velocities obtained by VSP analysis showing the accuracy of the method. Results showed that the fast shear waves polarised at an azimuth of 120˚ in Lambert 9 which was not far from that obtained by [12] and 150˚ observed in Satyr 1was in agreement with observations by [5] for the principal maximum horizontal stress directions in the North-West Shelf. P wave polarisation was observed to be unstable, tools with orientation sensors would be required to obtain reliable estimates of fast and slow shear wave polarization azimuths. The knowledge of fracture orientation and stress fields in the North-West Shelf is very necessary in building accurate seismic velocity models, as such, continuous anisotropy investigations of anisotropy is recommended for proper characterisation of sub-surface structures.

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