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The Stybarrow Field – a 4D Case Study

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SUMMARY

The Stybarrow oil Field was discovered in 2003 in the Exmouth Sub Basin, offshore Western Australia, with production starting in November 2007. A 4D seismic modelling study conducted early in the field's life indicated that 4D at Stybarrow would be important for reservoir monitoring. The modelling indicated that changes in reservoir pressure caused by water injection and changes in water saturation caused by reservoir depletion should be observable on 4D seismic data. The first monitor survey at Stybarrow was recorded in November 2008, 12 months after the start of production and a second monitor in May, 2011.

Geophysical challenges at Stybarrow included very strong azimuthal anisotropy, variable acquisition directions and strong currents. Azimuthal anisotropy produced large artefacts and needed to be corrected to extract useful 4D information from the data.

The results of the surveys were in agreement with the 4D modelling and a development well was drilled on the basis of the first monitor survey. The 4D surveys have proven to be an important tool at Stybarrow for optimal reservoir monitoring and production.

Key words: 4D, time lapse, anisotropy, Stybarrow.

INTRODUCTION

The Stybarrow oil Field is located offshore Western Australia in the Exmouth Sub Basin, approximately 45km offshore in 800m of water (Figure 1). The field was discovered in 2003 and production started in 2007. The oil is contained within Cretaceous aged, excellent quality, turbidite sandstones (Hill, *et al*., 2008).

The Stybarrow Field shows clear DHI's including brightening caused by oil and a down dip conformance to structure. The presence of DHI's, combined with faulting within the field that potentially compartmentalise the field, makes Stybarrow a good candidate for reservoir monitoring using the 4D seismic method. Two 4D monitor surveys have been recorded at Stybarrow (Hurren, *et al*., 2012).

In this paper, we first describe a 4D modelling study that examines the application of 4D at Stybarrow. Next, we describe the acquisition design of the 4D followed by the seismic processing of the data. Lastly, the 4D interpretation of the seismic surveys is presented.

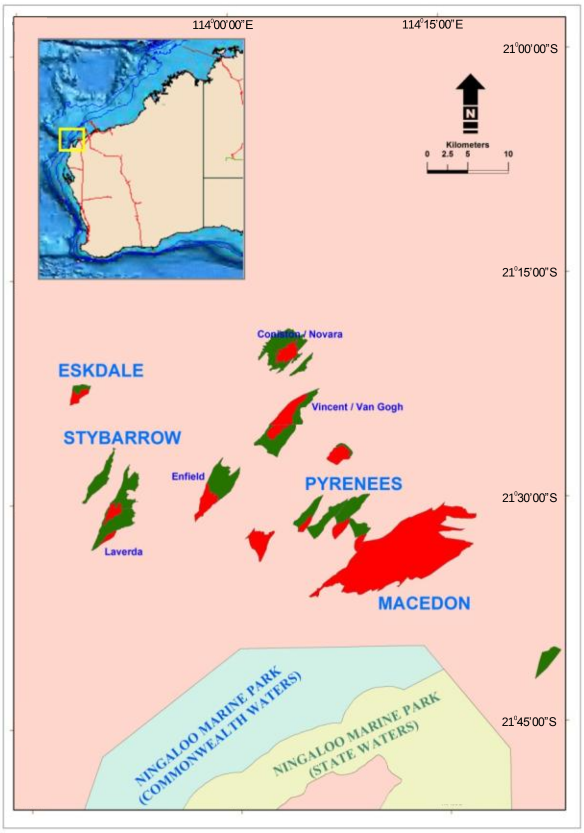

Figure 1. Map showing the location of the Stybarrow oil Field, offshore Western Australia.

METHOD AND RESULTS

The 4D project at Stybarrow consisted of four main stages. First, we conducted a 4D modelling study to see whether it would be possible to detect predicted changes in pressure and saturation in realistic noise conditions at Stybarrow. Next, we used the results of the study to determine the most appropriate acquisition parameters for the survey, which were then used to acquire the survey. Thirdly, a 4D-specific processing flow that also corrected for the effects of azimuthal anisotropy was developed and applied to the data. Lastly, the 4D data were interpreted and used to position a production well on the field.

4D Modelling

The 4D modelling study was performed to predict the 4D signal at Stybarrow and determine if it would be measurable above 4D non-repeatable noise. The 4D noise was estimated using the existing 3D prestack seismic data at Stybarrow from a regional survey recorded in 2001. We estimated the NRMS noise as a function of |Dsrc|+|Drec| for a number of different 4D acquisition geometry scenarios.

The 4D signal was estimated by building a 3D model based on the geological static model of the reservoir. The model was populated with elastic properties obtained from a rock physics study using the Stybarrow well data. This enabled an estimate of Vp, Vs and density of the sands to be made as a function of fluid type and pressure using an effective stress relationship.

The sands at Stybarrow are buried approximately 1500m below the sea floor and have high porosities. They have lower acoustic impedance than the encasing shales, and show up as bright events with a relatively flat AVO response when saturated with water. Oil saturation produces brightening of approximately 50 percent, and changes the AVO response from a flat response to a weak Class III response (Figure 2).

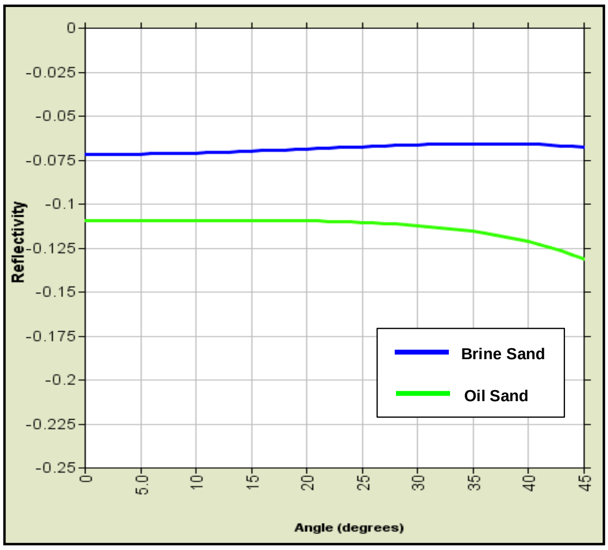

Figure 2. AVO single interface response for an oil saturated and brine saturated reservoir sandstone.

The 3D reservoir model was converted to angle stack seismic volumes via the Aki-Richards approximation and convolution with an extracted wavelet. Reservoir flow simulations were combined with rock properties via Gassmann fluid substitution and a velocity-pressure relationship, enabling 3D angle-stack synthetic seismograms to be created for various flow simulation time steps.

4D difference maps were created by doing amplitude extractions on the 3D synthetic seismograms for a number of different time steps. Band-limited random noise was added to simulate the effect of 4D noise for different acquisition geometries. Analysis of the results suggested that useful 4D signal should be measurable after 12 months of production.

Seismic Acquisition

The 4D modelling study showed that it was important to suppress 4D noise by keeping |Dsrc|+|Drec| to a minimum. However, the pre-production 3D over Stybarrow was not a dedicated baseline survey, but was part of a large regional survey recorded in 2001. The survey was not optimal as a 4D baseline.

The 2001 seismic survey was recorded east-west. Recording a monitor survey in this orientation would leave an acquisition hole over a key part of the field due to the location of the Stybarrow Venture FPSO. Alternatively, undershooting could be used, but this would produce variations in shot-receiver offset and azimuth which would increase the 4D noise. A further problem is the presence of strong and variable currents that produces large cable feather. This makes it difficult to reproduce source and receiver locations using a conventional single vessel acquisition methodology. Non-repeatability due to undershooting, cable feather and shooting directions is greatly exacerbated by the strong azimuthal anisotropy.

The acquisition geometry we chose did not replicate the geometry of the 2001 survey, but instead was designed to be recorded parallel to the main fault trend of the field in a NNE direction. This acquisition geometry is not optimal for the first monitor survey but is the optimal direction for future monitor surveys. It coincides with the slow azimuthal anisotropic axis and produces full fold, narrow azimuth, coverage over the entire field. In addition, the survey was recorded with separate source and receiver vessels in a push-pull mode. This reduces infill and 4D noise caused by cable feather (Ridsdill-Smith, *et al.*, 2007).

Azimuthal Anisotropy and Seismic Processing

Strong azimuthal velocity anisotropy is observed at Stybarrow, with fast and slow Vp values in sands differing by 10-20 percent. Anisotropy at Stybarrow has been measured though shear wave splitting in dipole sonic logs and VSPs (Pevzner, *et al*., 2009) and through the analysis of seismic velocities. Its effect on azimuthal AVO is given in Brajanovski, *et al*. (2009). Azimuthal anisotropy is only observed within the sands, and is limited to the reservoir sands and overburden sands.

Figure 3 shows a NMO corrected super gather that was merged from the baseline and monitor survey for the same CDP location. The gather has been NMO corrected using a velocity derived from the 2009 monitor survey. There are very large timing differences (>50ms) between the two surveys at the far offsets (for example, see the event at 2125 ms) which are caused by azimuthal anisotropy.

The methodology we used for measuring and removing the effects of azimuthal anisotropy is given in Bishop, *et al*. (2010). It uses a cross-correlation based method to estimate the strength and direction of anisotropy which is applied to the data using elliptical anisotropic move-out (Corrigan, *et al*., 1996). This is followed by azimuth independent inverse NMO and a conventional prestack time migration processing flow.

4D Interpretation

The 4D modelling study showed a number of seismic responses that could be observable between the baseline and monitor surveys. A strong decrease in acoustic impedance could be caused by either a pressure increase within the reservoir due to water injection, or by gas evolving due to a pressure drop close to the producers. A moderate increase in acoustic impedance could be caused by an increase in Sw during reservoir depletion. The change in seismic response caused by a pressure drop alone would likely be below the noise threshold.

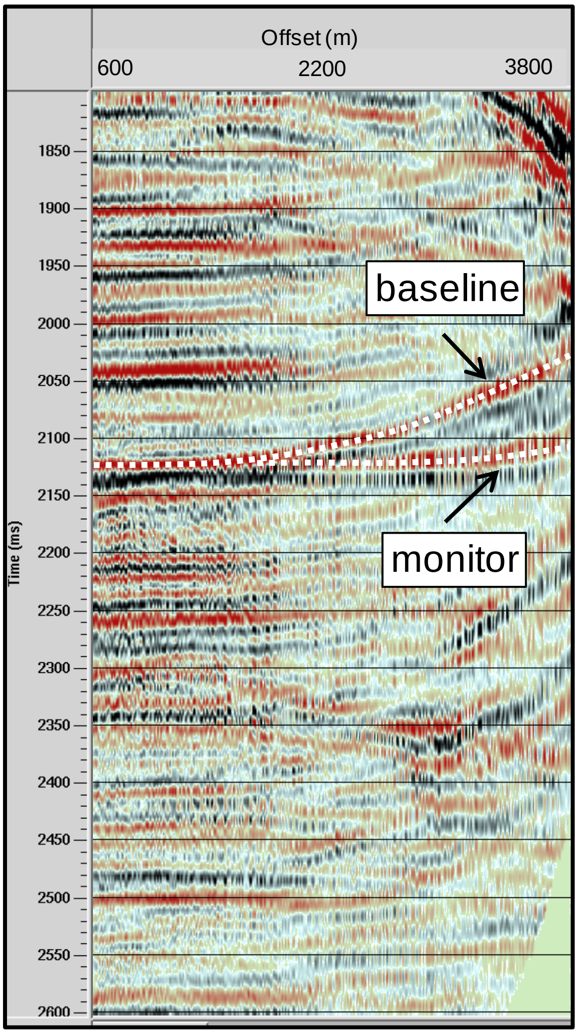

Figure 3. Merged super gather for the baseline and monitor surveys. The gather has been NMO corrected using the velocity derived from the 2009 monitor survey.

4D AVO analysis can discriminate between pressure and saturation changes (Lumley *et al*., 2003). Pressure changes are best detected at near offsets and saturation changes at far offsets. For a decrease in acoustic impedance, 4D AVO is used to differentiate between an increase in reservoir pressure and gas coming out of solution. Increasing the reservoir pressure reduces the AVO gradient, changing the AVO to a Class IV response. Gas coming out of solution increases the AVO gradient and changes the AVO to a stronger Class III response, as shown in Figure 4.

Figure 5 shows the 4D difference map of the near angle stack for the baseline and first monitor surveys. The map was created by extracting the maximum negative amplitude at the top reservoir event on the baseline and monitor surveys, followed by subtraction of the monitor amplitude map from the baseline amplitude map. The producing intervals of the horizontal production wells are marked by the green bars and the water injection wells by the red circles. The northern production well had not been drilled at the time of the monitor survey. The initial OWC is marked by the white dotted line.

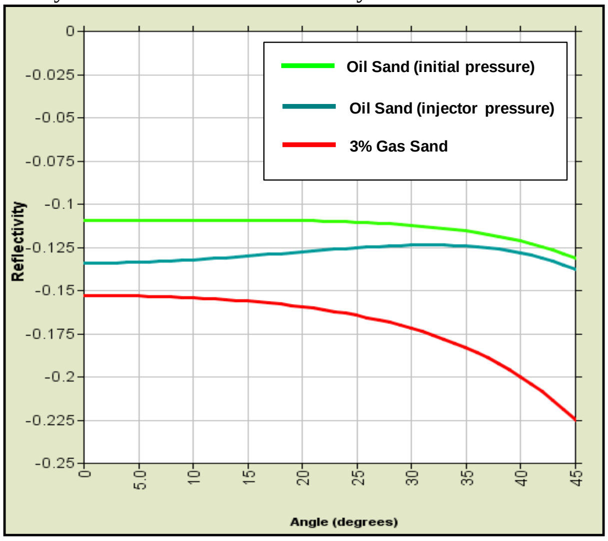

Figure 4. AVO single interface response for: an oil saturated sand at initial pressure; an oil saturated sand at injector pressure; and an oil sand with 3% gas saturation.

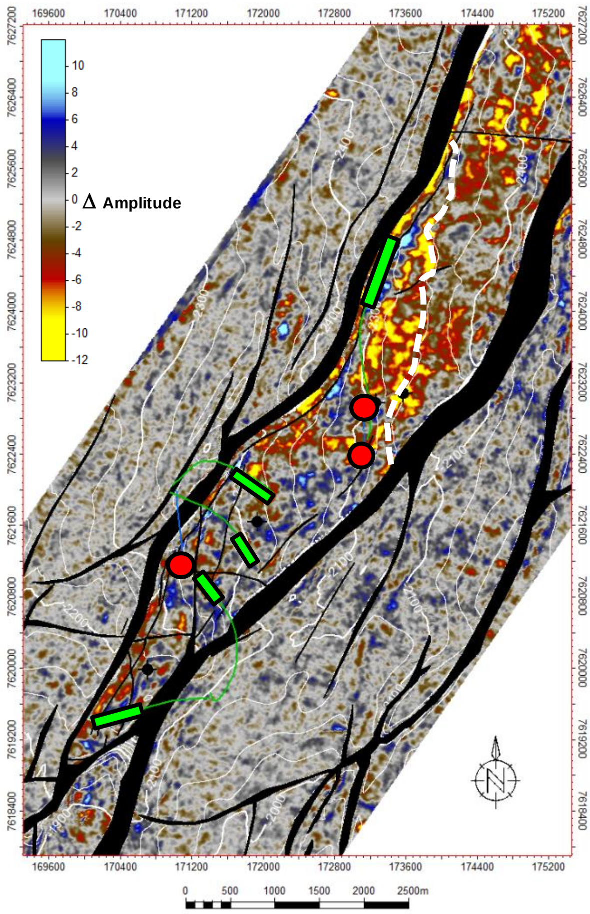

Figure 5. 4D difference map of the near angle stack for the baseline and first monitor surveys.

The main observation from Figure 5 is that the 4D signal is limited to between the two NNE trending faults that bound the Stybarrow field. This indicates that there is a good 4D signal-to-noise ratio at Stybarrow. Within the Stybarrow field, there is a decrease in acoustic impedance to the north, down dip from the two northern water injection wells, as indicated by the red and yellow amplitudes. This is caused by an increase in reservoir pressure and suggests the aquifer is not well connected further north. There is an increase in acoustic impedance within the central part of the field indicated by the blue amplitudes. This corresponds to an increase in Sw caused by water injection and reservoir depletion.

Figure 6 shows the 4D difference map of the far angle stack for the baseline and first monitor surveys. The bright yellow and red events close to the three central horizontal production wells are most likely caused by gas coming out of solution. As predicted by the modelling, the water signal is stronger on the far angle difference maps. In particular, a strong water signal can be observed between the southern-most water injector and production well.

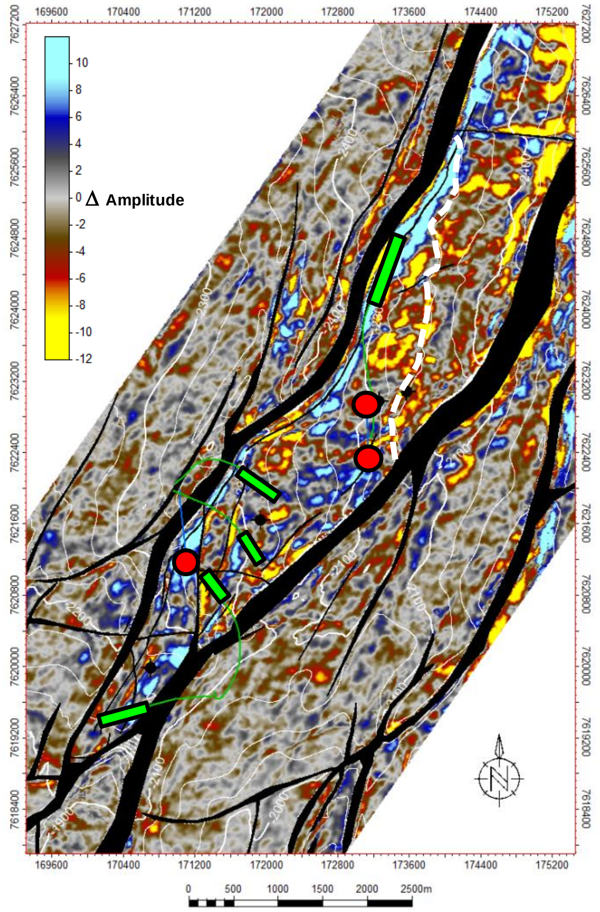

Figure 6. 4D difference map of the far angle stack for the baseline and first monitor surveys.

The strong 4D pressure signal in the northern part of the field shows that this part of the field is pressure supported by the northern water injector well. This de-risked further developing this part of the field and also supplied qualitative pressure information to allow for the safe drilling of an additional horizontal producer. The 4D seismic analysis also showed that there were no significant baffles within the field.

After the first monitor survey in 2008, a second monitor was recorded in 2011 to assist potential infill drilling. This survey was acquired with acquisition parameters identical to the first monitor, resulting in a 50 percent drop in NRMS noise relative to the first monitor. Significant information was obtained for updating the static and dynamic reservoir models (Hurren *et al*., 2012). The survey indicated that the field was being drained as planned.

CONCLUSIONS

A strong 4D seismic signal has been measured at the Stybarrow oil Field, and the method has been used successfully for reservoir monitoring and development. The first monitor was used to aid in the placement of a development well. The second monitor showed that the field was being drained as planned.

The key components for the success of 4D at Stybarrow were 4D modelling, innovative acquisition design and most importantly, 4D seismic processing to address the effects of azimuthal anisotropy.

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