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4D Seismic over the Pyrenees Fields

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SUMMARY

In this paper we present a case study of 4D seismic acquired over the Pyrenees Fields, offshore Western Australia. The Pyrenees trend was discovered with the drilling of the West Muiron-5 discovery well in 1993 which found oil and gas within the Pyrenees member sandstones. Production at Pyrenees started in 2010.

Before the start of production, a dedicated 4D baseline survey was recorded over the fields in 2006. A detailed modelling study concluded that a 4D monitor survey would provide useful information for reservoir surveillance and infill drilling decisions. The monitor survey was acquired in 2013, and the overall quality of the 4D was excellent with high 4D signal strength and low 4D noise.

The 4D response at Pyrenees is broadly consistent with the modelling. The main response is softening of the reservoir caused by gas coming out of solution produced by a pressure drop within the reservoir. The 4D response to changes in oil saturation is small. Incorporating the 4D interpretation into field development is ongoing, and so far it has been useful for refining the stratigraphic model, determining fault seal integrity, and determining the sealing capacity of intra-field faults.

Key words: 4D, time lapse, Pyrenees, acquisition, processing, interpretation.

INTRODUCTION

The Pyrenees Fields are located in the Exmouth Sub-basin, offshore Western Australia in approximately 200m of water (Figure 1) at a depth of approximately 1200m below sea level. They consist of a series of oil and gas accumulations within structural-stratigraphic traps, reservoired within Cretaceous aged sandstones of the Pyrenees Member. The "Pyrenees Trend" was discovered in 1993 with the drilling of the West Muiron-5 discovery well (Scibiorski, *et al.*, 2005) and production started in 2010. Overall, the depositional system of the Pyrenees Member is described as a wave dominated delta (Woodall and Stark, 2013).

The Pyrenees Fields show up as amplitude anomalies on seismic data, with elevated amplitudes associated with hydrocarbons, down-dip conformance to structure and flat spots at fluid contacts. A 4D seismic baseline survey was recorded over the fields before the start of production and a 4D monitor survey three years into production.

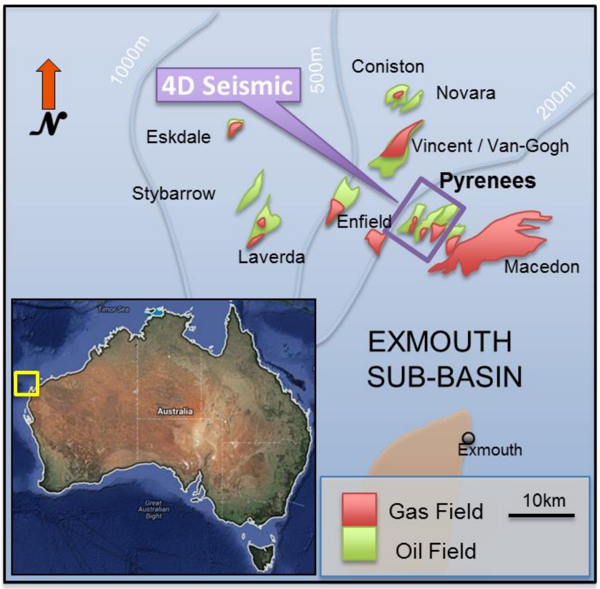

Figure 1. Map showing the location of the Pyrenees Fields.

This paper starts with a discussion on the acquisition of the 4D seismic baseline survey. Next it describes the rock physics and 4D modelling study that was important in justifying the acquisition of a monitor survey. This is followed by a discussion on the acquisition of the monitor survey and 4D seismic processing of the data. Lastly, we discuss some early interpretation of the results.

METHOD AND RESULTS

Design of the Baseline Survey

A 3D survey was recorded over the Pyrenees Fields as well as nearby drilling opportunities in 2006. The purpose of the survey was twofold: (1) record a modern 3D seismic survey to aid field development and outline nearby development opportunities; and (2) record a 4D baseline survey over the Pyrenees Fields to help with future reservoir monitoring and infill drilling. The acquisition of the 4D baseline survey is discussed in Woodward, *et al*. (2006).

Strong and variable currents in this region of the Exmouth Sub-basin produce unpredictable streamer feathering. This is particularly a problem for 4D seismic, since it is important to have good positional repeatability for the baseline and monitor surveys. The methodology adopted for this survey was to record the survey with overlapping sail lines, using 12 streamers with a move-up of eight streamers (see Figure 2 below and Woodward, *et al*., 2006).

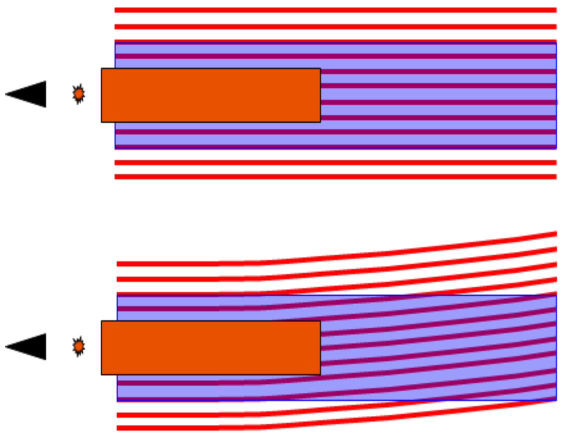

Figure 2. Overlapping sail lines using 12 streamers and an eight streamer move-up.

A major source of 4D noise is the magnitude of the source and receiver mis-positioning errors between the monitor and baseline surveys (ie, |Dsrc|+|Drec|). For 4D seismic data that has overlapping streamers on the baseline and monitor surveys, the magnitude of |Dsrc|+|Drec| depends mainly on the streamer spacing. To keep |Dsrc|+|Drec| to a minimum, we used tightly spaced streamers set to 50m separation. This results in a maximum value for |Drec| of 25m assuming overlapping streamers on the baseline and monitor surveys.

4D Modelling

Preliminary 4D modelling was conducted before the acquisition of the 2006 baseline survey which indicated that the Pyrenees Fields were good candidates for the 4D seismic method. A more detailed 4D modelling study was conducted before the acquisition of the monitor survey and played a significant role in justifying the acquisition of the monitor survey.

The 4D modelling consisted of a number of steps. Firstly, a rock physics study was undertaken to predict the changes in elastic properties as a function of changes to reservoir conditions such as changes in fluid saturations. Next, we created a 3D synthetic seismogram based on the 3D geological model. This used rock physics transforms that converted geological based information such as porosity and Vshale to elastic properties. We also created a 3D synthetic seismogram using reservoir flow simulations corresponding to the approximate planned date of the monitor survey. Lastly, the modelled synthetic seismograms for the baseline and monitor surveys were used to predict the 4D seismic response.

A key part of the 4D modelling was estimating the effect of gas coming out of solution as the field began production. This was predicted to happen in areas where the reservoir pressure had been reduced to below the bubble point of the oil. Figure 3a shows the modelled oil saturation at the planned date of the monitor survey. Figure 3b and 3c shows that the 4D response depends on how the gas coming out of solution mixes. For patchy mixing, changes in oil saturation will dominate the response, while for homogenous mixing the gas coming out of solution will dominate the response. However, in either case, we concluded that useful production related information would be obtained to justify the acquisition of the monitor survey.

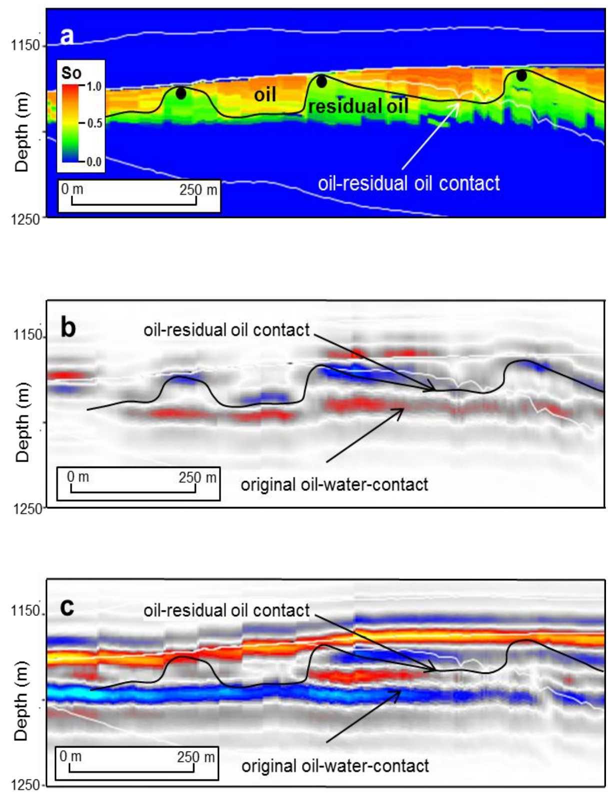

Figure 3. 4D modelling showing an arbitrary line through the Pyrenees Fields. (a) Modelled oil saturation at May 2013; (b) 4D seismic difference assuming patching mixing of gas; and (c) 4D seismic difference assuming homogenous mixing for gas.

Acquisition of the Monitor Survey

The design constraint for the monitor survey was to match the baseline survey as closely as possible. The main change between the baseline and monitor surveys was the use of broadband, PGS Geostreamer acquisition for the monitor survey. We chose the broadband technique on the basis that it would provide an improved 3D image over the Pyrenees Fields and surrounding area, including a number of fields not yet in production. However, broadband acquisition meant that for 4D processing the data needed to be filtered back to the equivalent conventional towed streamer acquisition. This approach is described in Day, *et al*. (2010). Sando (2012) concluded that the approach is comparable or slightly poorer than conventional-conventional streamer acquisitions.

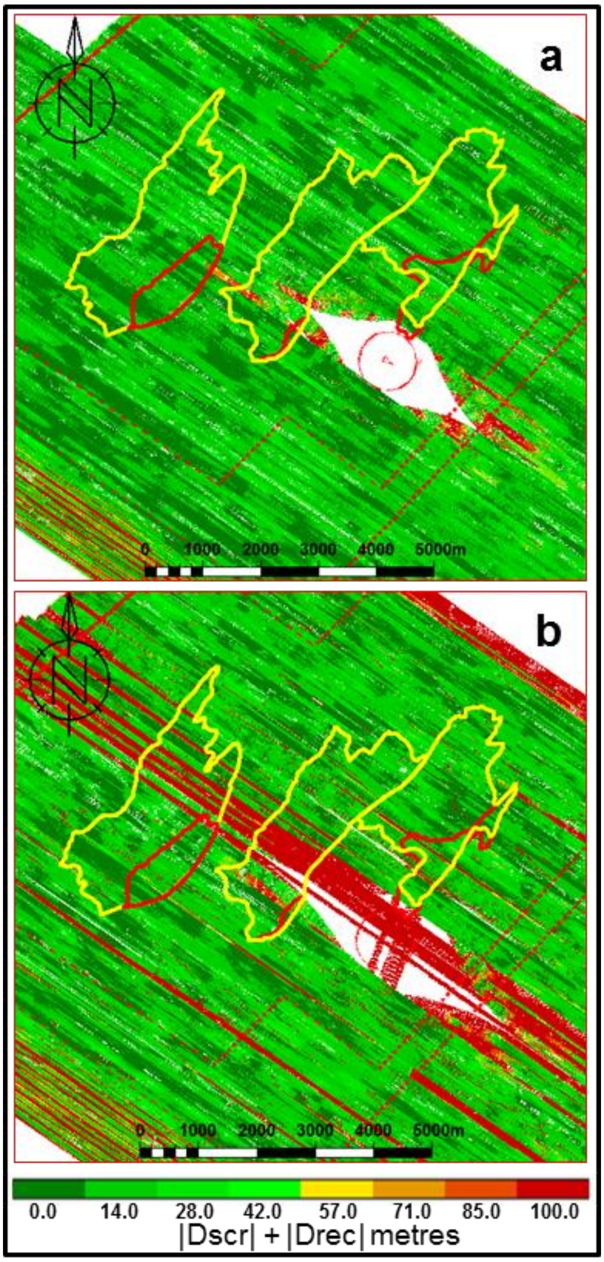

Figure 4. Map of |Dsrc|+|Drec|) for: (a) 300m to 350m offset range; and (b) 1450m to 1500m offset range.

Figure 4 shows maps of |Dsrc|+|Drec| for the near offset range and for the far offset range. In both cases, over most of the survey |Dsrc|+|Drec| is 28m or less. However, for the far offset range, a portion of the survey has mis-positioning errors over 100m. This corresponds to areas where streamers on the baseline survey did not overlap with the streamers on the monitor survey. This was largely the result of strong currents and acquisition difficulties associated with the location of the FPSO just to the south of the fields.

Seismic Processing

The processing of the baseline and monitor survey followed a conventional 4D processing flow including NRMS noise analysis at major processing steps. Two variations from the conventional flow were: (1) filtering back the broadband data to a conventional streamer acquisition (described in Day, *et al*., 2010); and (2) correcting for the effect of azimuthal anisotropy that is present in this area of the Exmouth Sub-basin. The method for measuring azimuthal anisotropy is based on a new technique applicable for narrow azimuth acquisition and is described in Cai, *et al*. (2014). The correction was applied before prestack depth migration using the method of Corrigan, *et al*. (1996).

Figure 5 shows the final outputs of 4D processing for a line though the Ravensworth-1 well. Brightening can be observed at the top reservoir event on the monitor relative to the baseline within the oil leg and dimming within the gas leg. Overall, the signal strength on the difference stack is strong relative to the 4D noise. The overall 4D noise level calculated using the NRMS method is approximately ten percent.

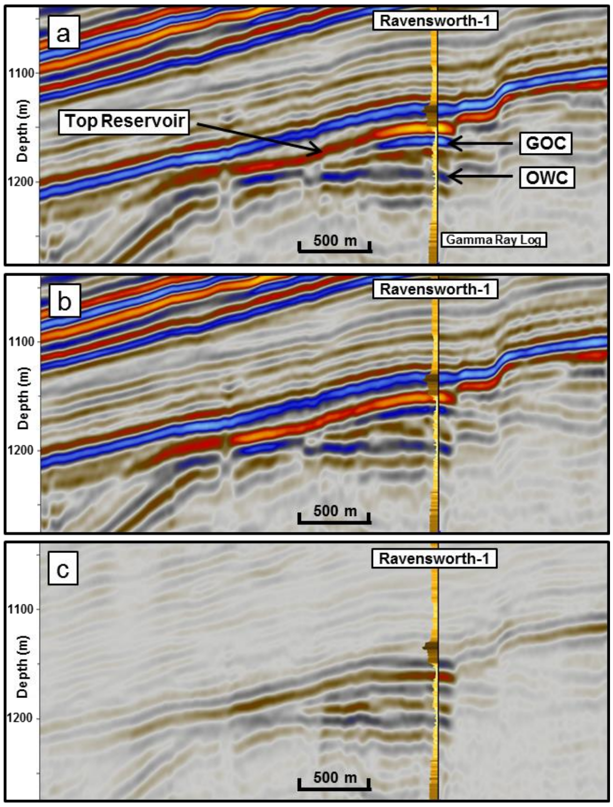

Figure 5. A seismic section through the Ravensworth Field for the baseline survey (a), the monitor survey (b), and the 4D difference stack (c). Polarity is such that in increase in acoustic impedance is blue.

Interpretation

The 4D response is broadly consistent with the rock physics analysis and modelling. Softening caused by gas coming out of solution in the oil leg is the strongest effect, as well as hardening caused by gas being replaced by oil as the gas caps in each field are blown-down. We also observe a weak pressure effect caused by pressure depletion as well as a weak response produced by replacement of oil by brine.

The effects of gas coming out of solution in the oil leg and replacement of gas by oil in the gas leg are clearly observable on the map in Figure 6. 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 baseline amplitude map from the monitor amplitude map. The horizontal producing wells are marked in green and the field outlines in yellow. Red and yellow amplitudes indicate softening of the reservoir and blue amplitudes indicate hardening of the reservoir.

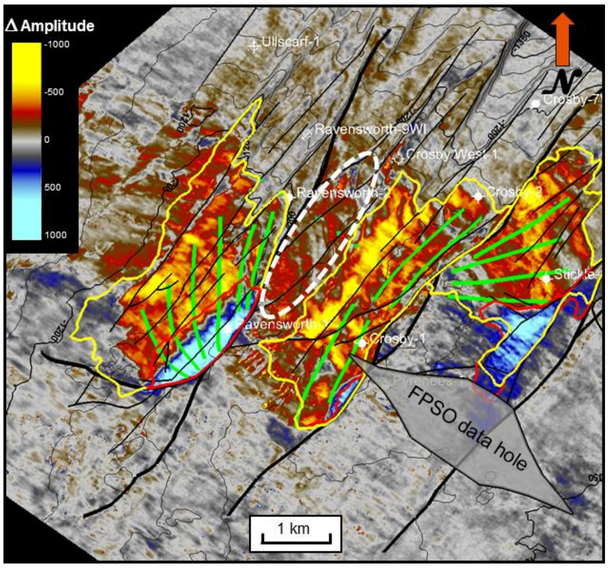

Figure 6. 4D difference map created on the top of the reservoir horizon.

The 4D response is also a function of reservoir quality, primarily permeability, and this has been used to refine the stratigraphic model. In addition, the 4D has proved useful in determining fault seal integrity, and whether or not intra-field faults may be partially sealing. The interpretation of the 4D is ongoing.

An unexpected response was 4D amplitude differences outside of the producing fields. For example, we observe 4D softening within undeveloped fields. This likely indicates pressure communication of the producing fields with the undeveloped fields through the extensive aquifer causing gas to come of solution within the oil leg. This effect can also be used to de-risk near field prospects. We also observe 4D responses in parts of the reservoir interpreted to contain only brine. For example, the region marked by the white dashed oval in Figure 6 shows strong 4D softening but is outside the closure of the Pyrenees Fields. Water analyses of wells within the fields suggest that the brine legs are fully saturated with methane. It is likely that a pressure drop within the reservoir causes enough gas to come out of solution in the brine leg to produce the observed 4D response, although some oil saturation cannot be ruled out.

CONCLUSIONS

The 4D at Pyrenees is characterised by strong 4D signal and low levels of 4D noise. This was the result of careful design of the 4D acquisition and processing as well having a reservoir amenable for the 4D method. A detailed rock physic study meant that there were no major surprises.

The main 4D response is softening of the reservoir caused by gas coming out of solution within the oil column produced by a pressure drop within the reservoir. There is also hardening caused by replacement of gas by oil as gas caps are blown down. The interpretation of the 4D is continuing, however, the 4D has been useful for refining the stratigraphic model, determining fault seal integrity, and determining whether or not intra-field faults are sealing. We are also using the 4D to de-risk near field prospects.

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