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A time-lapse feasibility workflow incorporating core calibrated 4D rock physics models

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SUMMARY

Rock physics analysis is a useful tool in time-lapse seismic feasibility studies and can help to assess the effect of pressure and saturation changes on the elastic parameters which the seismic data is sampling. Calibration using velocity measurements made on dry core data at varying pressure conditions allows for forward modelling of the expected seismic response at different effective pressures and hydrocarbon saturation levels. In this study we show that incorporating pressure effects produces non-negligible changes to the elastic properties of the reservoir rock. Changes of up to 9-10% to acoustic and shear impedance respectively are observed in the most prospective reservoir interval and would be detectable by good quality 4D seismic data.

Key words: rock physics, time-lapse seismic, effective pressure, ultrasonic measurements

INTRODUCTION

Four-dimensional (4D) or time-lapse seismic data have proven to be a useful tool in observing changes in hydrocarbon bearing reservoirs over time and to aid in efficiently producing hydrocarbons from the subsurface. 4D seismic has provided excellent value to businesses in many regions and in diverse reservoir settings, however, the cost of such projects merits a detailed case by case technical justification, also called a sensitivity analysis by means of forward modelling. Jack (2017) and Blangy (2017) present several compelling examples of the positive impact 4D seismic on the business bottom line. Specifically, reports from Statoil (now Equinor) indicate that close to 75% of the fields it operates use 4D technology. Even one additional percent of hydrocarbon recovery there is worth about $23 billion. Case histories show that the performance of mature reservoirs can be positively and significantly affected by 4D technology. Interpretation of 4D seismic data ranges from fairly qualitative methods of observing changes in seismic reflectivity to modern, quantitative methods, such as prestack simultaneous amplitude versus offset (AVO) inversion. One benefit of pre-stack interpretation methods is the potential for decoupling the effects of changing water saturation and pressure. However, pre-stack methods typically require a higher signal-to-noise ratio which, for 4D seismic, is related to two key factors: seismic repeatability and seismic detectability. Seismic repeatability refers to the acquisition differences, specifically the minimisation of these, between the acquired seismic surveys, such that the only changes observed are due to changes in the producing reservoir. Detectability relates to how large the expected change in seismic amplitudes are due to changing reservoir conditions during production relative to the time-lapse noise level. Rock physics based synthetic forward modelling of the seismic-scale elastic attributes helps assess this detectability and also determine what to look for and how in repeated seismic surveys. This is the topic we focus on in this work. Multiple publications (e.g. Blonk et al. 2005; Caspari et al. 2015; Ghaderi and Landro., 2009; Smith et al. 2008, Suman and Mukerji; 2013) present case studies based upon the evaluation of the seismic response due to pore fluid changes during production. It appears that not only these changes, but also variations in pore pressure can be largely responsible for expected time-lapse variations in the seismic attributes. Here we offer a workflow that incorporates both effects. Beach Energy is investigating the feasibility for 4D seismic to detect fluid and pressure changes in the Thylacine and Geographe gas fields located in the offshore Otway Basin, Australia. This paper discusses the results of the preliminary rock physics study undertaken in collaboration with Qeye. We utilize wireline data to assess the effects of fluid changes and laboratory velocity versus differential confining stress measurements to quantify the effects of pore pressure variations. The latter effect is shown to be dominant in this detectability case study.

METHOD AND RESULTS

Several authors (Blonk et al. 2005; Caspari et al. 2015; Ghaderi and Landrø, 2009; Smith et al. 2008, Suman and Mukerji; 2013) have published case studies where the expected change in the elastic properties of the target rock is forward modelled via fluid substitution of the reservoir pore space. For example, the change in elastic properties when replacing hydrocarbons with another fluid such as brine (Blonk et al. 2005) or even replacing brine with carbon dioxide when assessing the feasibility of geosequestration (Caspari et al. 2015). Both Avseth et al. (2005) and Dvorkin et al. (2014) propose a workflow to also incorporate pore pressure changes into the analysis. The availability of velocity measurements on dry core data, conducted at ultrasonic frequencies, allows us to derive separate functions for P and S-wave velocities relating the dry rock velocity to the effective pressure:

$$V_p(P_{eff2}) = V_p(P_{eff1}) \cdot \frac{1 - A_p \cdot e^{\left(\frac{-P_{eff2}}{P_{0P}}\right)}}{1 - A_p \cdot e^{\left(\frac{-P_{eff1}}{P_{0P}}\right)}} \qquad (1)$$

$$V_s(P_{eff2}) = V_s(P_{eff1}) \cdot \frac{1 - A_s \cdot e^{\left(\frac{-P_{eff2}}{P_{0S}}\right)}}{1 - A_s \cdot e^{\left(\frac{-P_{eff1}}{P_{0S}}\right)}} \qquad (2)$$

where P_{eff2} is the new effective pressure, P_{eff1} is the initial effective pressure and A_p, A_s, P_{0P} and P_{0S} are empirical constants. An implicit assumption made is that the velocities depend on the effective pressure (Biot and Willis, 1957):

$$P_{eff} = P_c - \alpha P_{pore} \tag{3}$$

where P_{eff} is the effective pressure, P_c is the confining pressure and P_{pore} is the pore pressure. The coefficient α, which scales the effect of pore pressure, is the Biot-Willis coefficient:

$$\alpha = 1 - \frac{K_d}{K_{solid}} \tag{4}$$

where K_d is the effective dry rock moduli and K_s is the effective moduli of the solid phase. These velocity-pressure functions allow us to calculate the dry rock moduli, assuming density is invariant, at any effective pressure. We can then use the Batzle and Wang (1992) relations to update the pore fluid bulk modulus and density at the new pore pressure and subsequently apply Gassmann fluid substitution (Gassmnan, 1951) to calculate the saturated rock bulk modulus at the new pressure:

$$\frac{K_{sat2}}{K_{mineral} - K_{sat2}} - \frac{K_{fluid2}}{\phi(K_{mineral} - K_{fluid2})} = \frac{K_{sat1}}{K_{mineral} - K_{sat1}} - \frac{K_{fluid1}}{\phi(K_{mineral} - K_{fluid1})} \tag{5}$$

where K_{sat2} is the bulk modulus of the rock saturated with fluid 2, K_{sat1} is the bulk modulus of the rock saturated with fluid 1, K_{fluid2} is the bulk modulus of fluid 2, K_{fluid1} is the bulk modulus of fluid 1, $K_{mineral}$ is the bulk modulus of the mineral and ϕ is porosity.

Two significant assumptions have been made; changes in velocity depend only on the effective pressure and density is invariant with changing effective pressure. Other assumptions made in the workflow, for simplicity, are:

- the reservoir remains below bubble point pressure;
- fluid mixing is uniform;
- that changes in the confining pressure on the core have the same effect as equivalent changes in the pore pressure in the reservoir;
- that the porosity is constant under the imposed pressure variations;
- the velocity measurements made on the core are representative of the velocity changes observed in the seismic bandwidth

Case study - Location and history

The Geographe (Block VIC/L23) and Thylacine (Block T/L2) fields lie in the Otway basin offshore Victoria, Australia. Production started in 2007 from Thylacine and 2013 from Geographe with production coming from the Flaxman/Waarre and Thylacine sandstone units. Baseline seismic predates production.

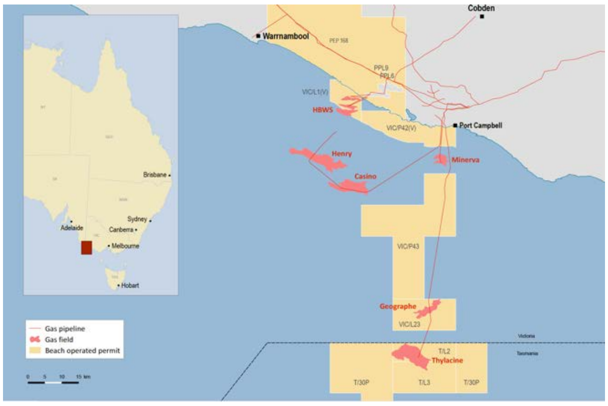

Figure 1. Location of the study area. The Geographe and Thylacine fields are the two southernmost fields shaded in red.

Laboratory data - Effects of stress variation

P−wave and S−wave velocity measurements at ultrasonic frequencies were made on dry core data by CSIRO under different effective pressure conditions and allowed the derivation of a velocity−pressure function of the form shown in equations (1) and (2) and compared with the observed velocities in Figures 2 and 3. This core data, extracted from wells within the Geographe and Thylacine fields, was supplemented by data from ultrasonic measurements conducted on core extracted from CRC-1; an onshore CO2 injection well drilled for the CO2CRC Otway Project (Wisman, 2012).

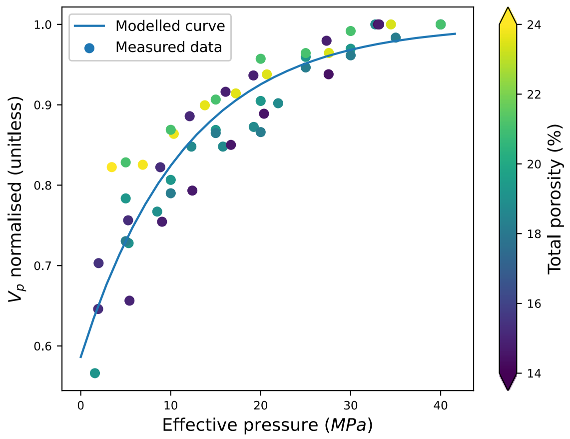

Figure 2. Modelled versus observed normalised P-wave velocities, colour coded by porosity, for all provided core samples.

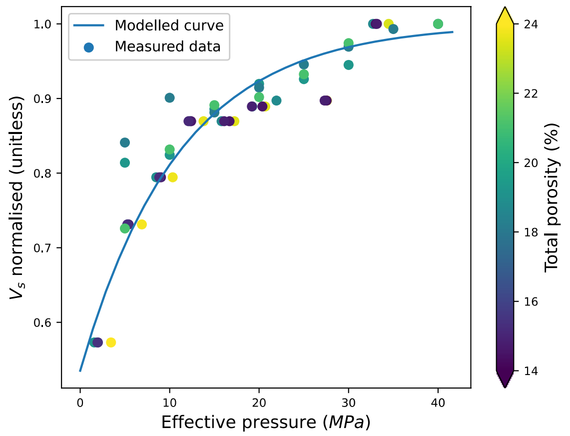

Figure 3. Modelled versus observed normalised S-wave velocities, colour coded by porosity, for all provided core samples.

Matrix pressure effects

The in-situ log data in the area of interest was then fluid substituted to the dry case using the provided petrophysics and fluid properties calculated using Batzle and Wang's relations. As shown below in Figures 4 and 5 the match between logged P-wave and S-wave velocities at dry conditions using Gassmann fluid substitution with the modelled velocity curves, from experimental data, is excellent.

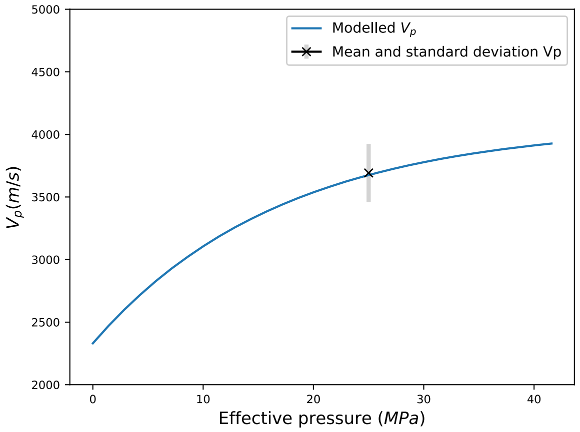

Figure 4. Modelled P-wave velocities from the dry core data versus P-wave velocities calculated using Gassmann fluid substitution of the in-situ log data at Geographe-1 to the dry case. The black cross represents the mean P-wave velocity in the substituted interval and the grey bar represents one standard deviation.

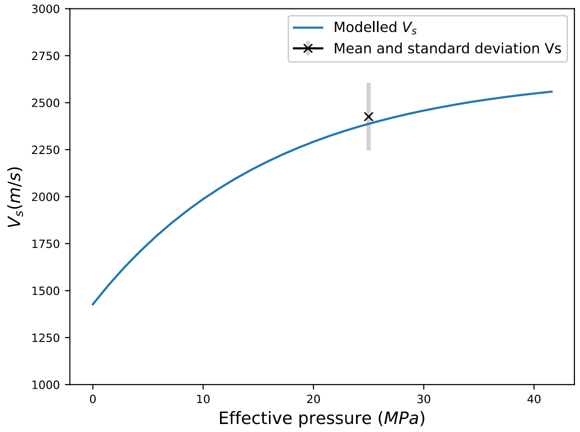

Figure 5. Modelled S-wave velocities from the dry core data versus S-wave velocities calculated using Gassmann fluid substitution of the in-situ log data at Geographe-1 to the dry case.

Fluid substitution and pressure effects

After calculation of updated dry rock velocities at new pressure conditions the fluid properties for each pressure-saturation scenario are calculated using Batzle and Wang's empirical relations and the new pore pressure. The pressure modified dry logs are then fluid substituted via Gassmann with the pressure modified fluid parameters at the modelled production saturation.

Acoustic impedance and Vp/Vs ratio variations

Figure 6 shows the results of the workflow in an AI vs. Vp/Vs crossplot at one of the wells in the study. The changes induced by the pore pressure depletion are a significant component of the entire modelled 4D response.

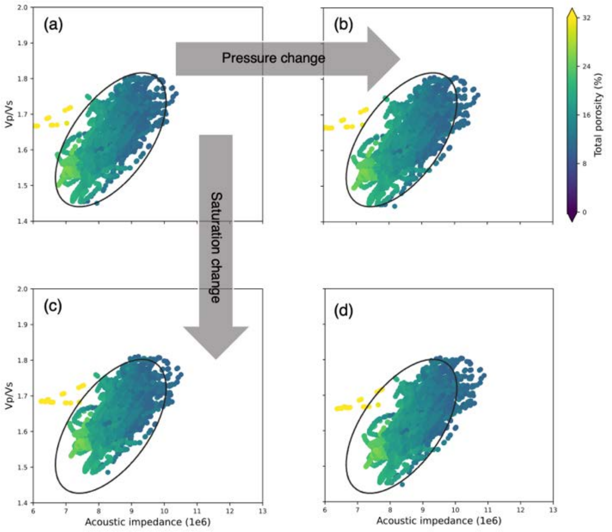

Figure 6. Thylacine-1 AI vs. Vp/Vs crossplot colour-coded by total porosity. Comparison of (a) base case, (b) modelled change in pore pressure of -20MPa, (c) modelled change in saturation +80% Sw and (d) both changed combined. Note that the change induced by the pressure depletion is significant and effects all porosities whereas the changes in fluid saturation have significant impact only in the high porosity sands.

CONCLUSIONS

Modelling shows that the expected change in the Flaxman/Waarre reservoirs is up to 9% for acoustic impedance (AI) and up to 9.5% for shear impedance (SI), and for the Thylacine reservoirs is up to 7% for AI and 7.5% for SI. In both units the production effects should be detectable on 4D seismic data. The pressure depletion makes a significant contribution to the 4D response across all porosities while the saturation changes mostly impact the higher porosity sands. Pressure depletion effects should be included in 4D modelling to fully understand the expected seismic response and properly assess detectability.

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