Title

4D stress sensitivity of dry rock frame moduli: constraints from geomechanical integration

Authors

Bloomer, D., Ikon Science Asia Pacific
Reynolds, S., Ikon Science Asia Pacific
Pavlova, M., Origin Energy Ltd
Taylor, R. Origin Energy Ltd
Sams, M., Ikon Science Asia Pacific

Abstract

In time lapse (4D) seismic studies, the impact of effective stress on the dry rock frame is difficult to constrain. The relationship between rock moduli and effective stress is dependent on rock properties, initial effective stress and the change in effective stress with time. A workflow is outlined to: 1) constrain laboratory and analogue data where significant variability is observed through use of well data; 2) provide initial effective stress and a time sensitive effective stress taking in to account the effects of pore pressure-stress coupling, where the stress state is not extensional. A time lapse feasibility case study in the Taranaki Basin, New Zealand is shown to demonstrate the sensitivity of these parameters, and indicate how uncertainties in bulk moduli and effective stress can then be quantified in the amplitude domain through modelling.

Introduction

Time lapse (4D) seismic describes the detection of changes in a reservoir through use of seismic data. In order for seismic data to have a time lapse response, variation in the elastic properties of the reservoir must be significant enough to be detected. Key reservoir factors include state of consolidation, porosity, stress sensitivity of the dry frame modulus, pore fluid phase and compressibility and reactivity of the minerals and fluids. Time lapse seismic feasibility analysis aims to quantitatively assess the potential for seismic detection of the reservoir based on rock physics principals. While not discussed further, equally important in producing a viable time lapse response are seismic attributes.

A number of authors have demonstrated the benefits of using time lapse seismic to highlight a number of reservoir phenomena, including water flood, bubble point dissolution and carbon sequestration. Such case studies are often associated with porosity reduction in compacted reservoirs or high porosity unconsolidated reservoirs. This study focuses on the impact of stress sensitivity on the dry rock frame moduli. In contrast to many published examples, feasibility is considered marginal, as porosities are moderate, the dominant principal stress is not vertical (i.e. not a continental margin) and stress-strain calibration data is not available.

Data

The study is focused on the southern Taranaki Basin, New Zealand. Reservoir deposits are mixed fluvial and lacustrine sediments, deposited by a north draining fluvial system, driven by Cretaceous-Eocene rift and sag phases. Amalgamated braided fluvial arkosic sandstone units have porosities of 11-19%. Both oil and gas are known to be present in the basin. The region has undergone a tectonic inversion, forming a number of bounding faults which provide up-dip lateral closure. Ambiguity exists within literature as to whether the basin stress state is normal, strike-slip or a combination of both, through evidence relating to neotectonic, earthquake, fault movement and earthquake focal mechanisms (Sherburn and White, 2006). Three wells were used to characterise rock framework and stress profiles on the basis of wireline, CPI, pressure and LOT/FIT data.

Variation of the dry rock framework

The impact of effective stress on the rock framework is difficult to constrain as stress sensitivity of sandstones is often considerable. While collection of laboratory stress sensitivity measurements is recommended, such data are not available in this study. MacBeth (2004) fit exponential regressions to a series of subsurface and outcrop data sets to relate the change in dry rock moduli to effective stress and is a useful conceptualisation of the underlying processes. Dry rock moduli increases exponentially as effective stress increases in response to closure of micro-cracks and pores, which decreases in sensitivity as the rock approaches the dry mineral moduli. Due to the absence of laboratory core measurements, a database is formed from reservoir and outcrop analogue models presented in the paper. The author recommends analogue selection is performed on the basis of clay volume and porosity, which are correlatable to the rate of moduli change per unit of pressure. Of analogues which exhibit similar clay volume and porosity to the reservoir, substantial differences in the dry rock moduli- stress relationship are observed for common basins, depositional environments, porosities and volume of clay. To help constrain this uncertainty and hence the analogues chosen, bulk and shear moduli are calculated from well data, which demonstrate a range of values valid at stress conditions at the time of data acquisition (Figure 1).

The assumption is made in this study that consolidation, porosity, compressibility and reactivity are not significant on the rock response. While the relationship between fluid properties and pressure is well understood, no change in pore fluid is considered at this stage in the interests of highlighting variation driven by changes in the rock framework alone.

Effective stress

To understand the variation of the dry rock framework in the context of our reservoir scenario, we require knowledge of the three principal stress magnitudes, both initial and following production (or an estimate if not available). A common limitation of laboratory stress sensitivity data is that measurements are made under uniaxial stress conditions, with an assumption made in extensional tectonic regimes that effective stress is equal to the overburden, as estimated through integration of the density data. In this study, as the maximum principal stress may not vertical if a strike-slip stress regime is present, the two remaining principal stresses are estimated through construction of a 1D geomechanical model. Effective stress is then assumed to be the mean of all principal stresses. Due to the ambiguity of the basin stress state, the effective stress is based on two end-member stress states, being normal and strike-slip tectonic regimes (Figure 1).

Pore pressure-stress coupling

Depletion of the reservoir causes a reduction in the pore pressure and a change in the maximum and minimum horizontal stress magnitudes. The pore pressure-stress coupling is predicted by poroelastic theory due to the elastic dilation of a porous rock and is observed in many depleted fields, being referred to as the reservoir stress path factor. Global measurements in the stress path factor commonly occur between 0.4 and 1.0 (Hillis, 2000). End-member stress path factor values of 0.4 and 1.0 are considered to capture the degree of uncertainty present.

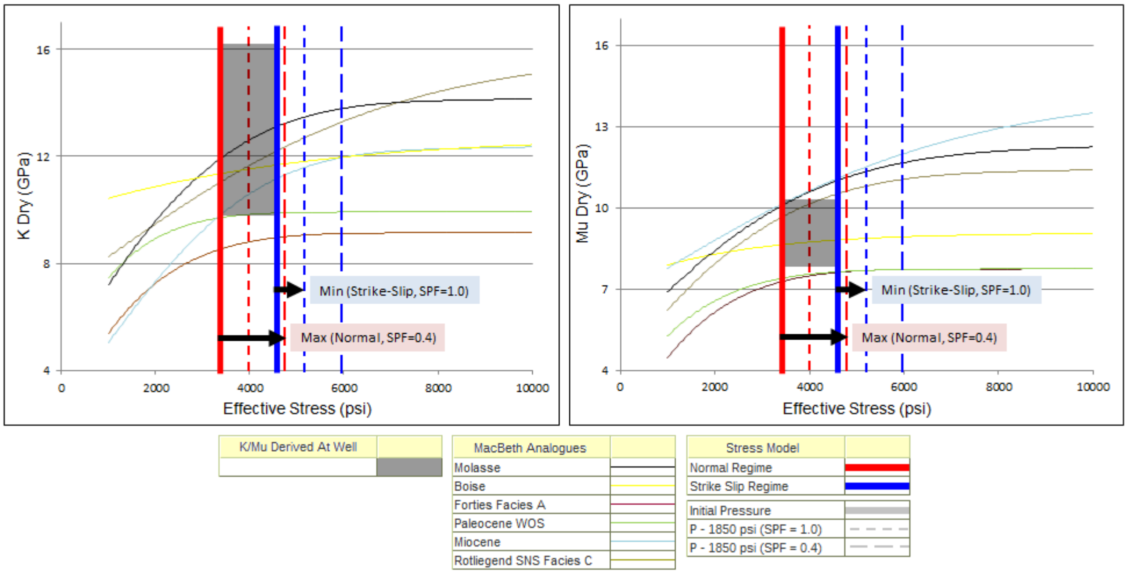

Figure 1 *MacBeth (2004) analogue effective stress - dry rock moduli relationships for bulk modulus (K, left) and shear modulus (Mu, right). The range of moduli derived from well data is shown over predicted initial stress range to help constrain uncertainty in the dry rock response. Changes in effective stress associated with all tectonic regime and stress path factor (SPF) cases are associated with a consistent drop in reservoir pore pressure of 1855 psi. Minimum and maximum changes in effective stress are highlighted with arrows.*

The impact of the stress regime and the pore pressure-stress coupling ratio is demonstrated in Figure1. In all cases, variation in effective stress is associated with a drop in reservoir pore pressure of 1855 psi, as estimated from production data. The most sensitive stress case on the rock framework will occur in the normal stress regime with a stress path factor of 0.4 (Δ1370 psi), and least sensitive in the strike-slip regime with a stress path factor of 1.0 (Δ660 psi). Variability modelled in absolute bulk modulus (K) varies from 1-7% and shear modulus from 3-11% dependant on the MacBeth analogue model, tectonic state and stress path factor assumed. It is observed the rock moduli variation caused through production is highly influenced by rock properties, stress path factor and initial effective stress, in response to the exponential form of the MacBeth type relationship.

Time lapse seismic modelling

Blocky modelling is performed to quantitatively assess time lapse seismic detectability associated with changes in the dry rock framework at differing random noise levels assumed present through variation in seismic repeatability. Figure 2a shows the input acoustic impedance (AI) model of the overburden-reservoir contact, where bulk and shear modulus in the reservoir increase laterally to the right. Time lapse AI reflectivity is shown in Figures 2b and 2c with the addition of 10 and 40% random noise respectively, representative of a typical noise level range associated with repeatability relative to the baseline response. Figure 2d shows trace attributes for RMS random noise at 10% (pink) and 40% (purple), and peak amplitude of the time lapse signal (blue). Assuming that the signal will be detectable at a signal to noise ratio of one for 3D seismic data, a change in bulk moduli of 1% is required for detection at 10% noise, and a change of 5% in bulk moduli at 40% noise. For 2D seismic data the signal noise ratio required would be far greater, as indicated by the difficulty in observing the time lapse response in section, particularly at the 40% noise level.

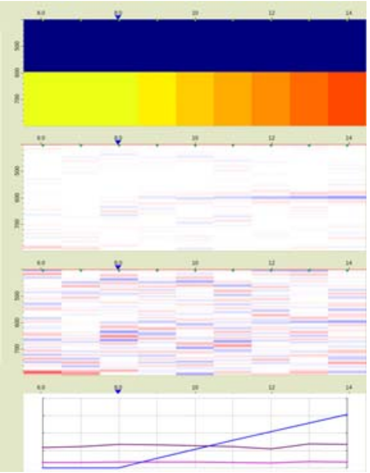

Figure 2 *Blocky model of overburden-reservoir contact where bulk and shear modulus are increasing to the right, (a) Acoustic impedance (AI) input, (b) AI reflectivity time lapse signal with inclusion of 10% random noise, indicative of excellent repeatability (c) AI reflectivity time lapse signal with inclusion of 40% random noise, indicative of poor repeatability (d) attributes shown at each trace for RMS random noise at 10% (pink), RMS random noise at 40% (purple) and peak time lapse signal amplitude.*

erv

Peak

Conclusions

The end-member scenarios presented in this abstract are considered equally probabilistic, and indicate a large degree of uncertainty is present. The sensitivity in the dry rock framework to the MacBeth analogue model selected highlights the importance of calibration data to constrain uncertainty where possible. Uncertainty in the stress regime can be reduced by additional data such as rock strength measurements and extended leak-off tests (XLOT). While field core analysis or reservoir analogue data is desirable, a combination of disturbance of the core through drilling, removal from in situ stress conditions, differences in scale between the core and seismic, and the potential for analogue core to misrepresent the formation, still may compound to form substantial uncertainty.

In any such study, significant uncertainty will exist in virtually all domains. To capture uncertainty in the dry rock stress-strain relationship, it is recommended to use multiple models, either to express the range of variability that exists within laboratory stress sensitivity data, or through analogues constrained using elastic moduli derived from well data. Stress sensitivity should be captured through use of end member overburden profiles in an extensional domain. For reverse, strike-slip and transitional domains, end-member stresses should be determined with additional consideration to the influence of pore pressure-stress coupling. Failure to consider the effect of pore pressure-stress coupling demonstrates significant potential to misrepresent time lapse seismic feasibility.

Potential for time lapse seismic detection is determined through seismic attributes and reservoir factors including stress sensitivity of the dry frame modulus and pore fluid phase. Where marginal sensitivity in feasibility is anticipated, modelling can be used to integrate rock property knowledge with seismic characteristics to quantify uncertainties in the amplitude domain. Consideration of other seismic attributes (inversion attributes) is recommended to boost potential time lapse effects. For example, gradient dependant attributes (Vp/Vs) and extended elastic impedance (EEI).

Acknowledgements

The authors would like to thank Origin Energy Resources Ltd NZ, Genesis Energy and Mitsui E&P Australia for permission to present these data.

References

Hillis R.R., 2000, Pore pressure/stress coupling and its implications for seismicity, Exploration Geophysics, 31(2), p 448-452.

Macbeth C., 2004, A classification for the pressure-sensitivity properties of a sandstone rock frame, 69(2), Geophysics, p 497-510.

Sherburn S., and White R.S., 2006, Tectonics of the Taranaki region, New Zealand: earthquake focal mechanisms and stress axes, New Zealand Journal of Geology and Geophysics, 49, p 269-279.