Building a 3D Geomechanical Model for the Fitzroy Trough

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SUMMARY

We present initial results from a physically self-consistent 3D geomechanical model for the Fitzroy Trough in the Canning Basin, Western Australia. Our research aims to improve the understanding of in-situ stresses in the trough, in particular the overall stress regime and spatial changes of the stress magnitudes due to basin geometry. We investigate the in-situ stresses first by utilising the classical “one-dimensional” approach to geomechanics and second by building a 3D geomechanical-numerical model. The boundary conditions of the 3D model are calibrated against stress data from wells within the trough. We show that the resulting overall stress regime is most likely strike-slip, although stress data from a small subset of wells would suggest a reverse faulting regime when considered in isolation. Further, basement depth and distance to basin boundary influence the stress magnitudes and lead to significant lateral variability of the stress magnitudes.

Key words: Numerical Geomechanics, In-situ Stresses, Canning Basin, Fitzroy Trough, Finite Element Method

INTRODUCTION

Classical approaches to geomechanics have significant limitations when assessing the orientation and magnitude of the in-situ stress field at the scale of a sedimentary basin. These classical approaches rely on “one-dimensional” analytical geomechanical models, which are models that incorporate stress and rock strength data along the trajectory of a borehole (Zoback, 2007). Although the stress tensor with three principle components is estimated with analytical and empirical methods, the variation of this tensor is only investigated in one dimension (i.e. the measured depth of the borehole). Estimations of the in-situ stress-field beyond the immediate vicinity of the borehole are based on interpolations and extrapolations. To assess the lateral variability of the 3D stress state a 3D geomechanical-numerical model is essential. For the numerical solution the Finite Element Method is suitable as it uses unstructured meshes to represent complex 3D model geometries and to achieve high numerical resolution in the area of key interest. Such models have been used to answer geomechanic and tectonic questions on the scale of tectonic plates (e.g. Rajabi et al., 2017) and on the scale of individual oil / gas / geothermal fields (e.g. Koutsabeloulis and Zhang, 2009). Numerical modelling at the intermediate basin scale requires the geological detail of a field scale model albeit over a much larger area and rock volume. Hence, only a limited number of basin scale numerical, 3D geomechanical models have been published (e.g. Ziegler et al., 2016).

Fitzroy Trough / Canning Basin

The Fitzroy Trough is one of two major NW trending depocentres in the Canning Basin of Western Australia. The Canning Basin is of substantial size (506 000 km$^2$) with 85% of it onshore. Deposition occurred over an extended period of time from the Early Ordovician to Early Cretaceous. The basin is relatively underexplored for its’ size and current hydrocarbon production is from Perm-Carboniferous sandstones and Devonian carbonates (GA, 2019). Please see Yeates et al. (1984) and Kennard et al. (1994) for a detailed introduction to the basin geology and Parra-Garcia et al. (2014) for a summary of structural features in particular the Fitzroy Trough.

Figure 1. World Stress Map data for the region. The study area roughly between 17° S 122° W and 19° S 124° W.

The Canning Basin is an area of moderate seismic activity (Glanville et al., 2014) and gradual shift in stress orientation is observable from the onshore section of the basin to the offshore section and adjacent offshore basins such as the Roebuck Basin (Heidbach et al., 2016 and see Figure 1). The geomechanics of the basin (i.e. in-situ stress field and constitutive rock properties) has practical ramifications including drilling challenges due to compressive stress regime, borehole stability issue, over-pressure and weak formations as well as completion challenges especially in regard to the stimulation of tight sands (see various well completion reports available from WAPIMS, 2019). Gholami et al. (2017) use the so-called “poroelastic method” to determine the in-situ stress field (based on one recent Canning Basin well: Asgard 1) with the result that the
predicted stress regime is reverse faulting. Published focal plane solutions, on the other hand, point towards a strike-slip regime (e.g. Broome; 23rd April 1979, Broome; 14th July 1979, Doubtful Bay; 6th February 1988 and Collier Bay; 10th August 1997; all in Leonard et al., 2002). If the stress regime is truly reverse faulting another limitation of the classic one-dimensional model has to be considered: stress measurements that are conventionally used to determine $S_{\min}$ (e.g. LOTs, Minifracs) are actually an estimate of the least principle stress, which only coincides with $S_{\min}$ in normal or strike-slip regimes. In a reverse faulting regime the least principle stress is $S_0$, which in turn is easily determined when density wireline logs (RHOB) are available. Hence, two independent stress measures (i.e. RHOB and LOTs/Minifracs) are collapsed into one principle stress estimate.

To address these challenges we first review available stress data from recent exploration wells drilled in the Fitzroy Trough. The classical one-dimensional geomechanics workflow is followed in this step. Then, in order to integrate all the available data into a physically consistent model we build a basin scale numerical 3D geomechanical model of the Fitzroy Trough. The model is based on a 3D geological model of the Fitzroy Trough provided by the Geological Survey of Western Australia (Parra-Garcia et al., 2014). The aim of this model is to improve understanding of the global stress patterns that are consistent with all observations. The aim is not to study local perturbations of the stress field due to faults or zones of mechanical weakness.

**METHOD AND RESULTS**

**1D Geomechanical Models**

We reviewed 20 wells drilled in the Fitzroy Trough, focusing on the most recent wells. First, we constrained the pore pressure and investigated if over-pressure was present at depth. The drilling experience in almost half of the study wells indicated over-pressure at depths greater than 2500mMD and rarely at depths shallower than 2000mMD. The overpressure indicators included splinterly cavings (e.g. Asgard 1, Yulleroo 2), high background gas and/or connection gas (e.g. Paradise 1, Valhalla 2, Yulleroo 3). The mud weights were increased to counteract this over-pressure and other borehole stability issues. Mud weights and direct formation pressure measurements are summarised in Figure 2.

The overburden or $S_V$ at a given depth $z_0$ is calculated by integrating the density $\rho$ from $z_0$ to the surface. The integral of the density is then multiplied by the gravitational acceleration $g$

$$S_V(z_0) = g \int_0^{z_0} \rho(z) dz$$

Wireline measurements of bulk density (RHOB) are available in all study wells, although the density values had to be extrapolated for shallow depths. An average overburden gradient is shown in Figure 3, as a solid black line. Drilling experience in almost all study wells indicate either a high differential in horizontal stresses or pervasive weak formations. These indicators include angular, blocky and tabular cavings, as well as numerous cases of “tight hole” or significant borehole enlargement. In some wells wireline runs could not be conducted over the planned intervals (e.g. Ungani 3, Valhalla 2). In this contribution we focus on leak-off tests (LOTs) as a measure for the least principle stress. We found eight (8) LOTs reported in the well completion reports with five (5) to be of high reliability. These are plotted in Figure 3 as blue asterisks; the blue solid line is an average trough these points. Three of these LOTs are below the averaged overburden gradient and so is the averaged LOT gradient. Therefore we refer to this gradient as the $S_{\min}$ gradient.

![Figure 2. Formation pressure constraints from wells drilled in the Fitzroy Trough compared with a hypothetical hydrostatic gradient (green dashed line).](image)

Careful review of the daily drilling reports lets us conclude that three of the LOTs did not reach the leak-off point and should be considered in information values similar to a formation integrity test (FIT). These are displayed as blue circles in Figure 3 and the values were not included in the calculation of the average $S_{\min}$ gradient. Further, all available FITs were plotted in Figure 3 as black crosses for completeness. It should be noted that all LOTs and FITs were conducted at depths that are above the usual onset of over-pressure.

![Figure 3. Average stress gradients for the overburden and $S_{\min}$.](image)
Modelling Workflow

The workflow to build the 3D geomechanical-numerical model can be subdivided into six steps. (1) The primary structural features and sedimentary surfaces of the geological model are extracted with GoCAD. (2) The structural features are used to define the geometry of the geomechanical-numerical model and HyperMesh is used to generate a finite element mesh on this geometry. (3) The python script ApplePy is used to assign the to the finite elements stratigraphic units based on the sedimentary surfaces. (4) The finite element solver ABAQUS and the tool FAST Calibration v1.0 is used to obtain the numerical the best-fit solution. (5) ABAQUS is re-run with the “best-fit” displacement boundary conditions. (6) Finally the Tecplot360 Add-on Geostress is used to analyse and visualise the model results.

As can be seen in Figure 4 the geological model is very detailed and has more than 50 faults defined. In order to reconcile the size of the numerical model (both sides of the trough, adjacent terraces and platforms are included) and complexity, the number of faults had to be reduced. We chose to only include the faults with significant offset in the numerical model; these are first and foremost the bound to only include the faults with significant offset in the numerical model and complexity, the number of faults had to be reduced. We chose to only include the faults with significant offset in the numerical model; these are first and foremost the bound faults of the trough (i.e. Broome Fault, Dampier Fault, Fenton Fault, Pinnacle Fault). The numerical model represents a volume of 350km x 220km and 10km deep and was meshed with 31 million tetrahedral elements (see Figure 5).


dedical Model – Fitzroy Trough

Figure 5. HyperMesh: Mesh details 31 Million Tetrahedral Elements

Figure 6. Cross section trough the Fitzroy Trough showing the distribution of the second invariant of the deviatoric stress tensor J2.

Initial results from our 3D numerical geomechanical model highlight the importance of basin geometry on the stress distribution (see Figure 6). In particular the depth to basement is influencing the stress field. Further, faults that juxtapose rocks with significantly different mechanical properties impact the stress field.

CONCLUSIONS

We conclude that (1) over-pressure is highly likely to be encountered at depths greater than 2500m. The lithological controls on over-pressure and the link to certain formations warrant further investigation. (2) The stress regime is at a transition between strike-slip and reverse faulting. The in-situ stress model by Gholami et al. (2017) results in a reverse faulting regime prediction. Review of all recent drilling data shows that most of the LOTs are below the overburden gradient, hence a strike-slip regime is also more likely. This is reinforced by the focal plane solutions in the area. At the same time two of the LOTs are actually above the overburden gradient. When considered in isolation the data from these wells suggest a reverse faulting regime. This highlights a general problem for building in-situ stress models in compressive tectonic regimes: LOTs will measure the least principle stress, but it is not a given that this is the $S_{\text{min}}$ and caution should be exercised when the LOT and overburden values are close to each other.

Initial results from the geomechanical-numerical model highlight the need to consider basin geometry in a geomechanical analysis. Further refinement of the model will help to (a) minimize drilling risk in the basin and (b) optimize wellbore stimulation designs based on the new knowledge of the in-situ stress field.

ACKNOWLEDGEMENTS

The authors would like to thank the Geological Survey of Western Australia for providing the 3D geological model of the Fitzroy Trough. Oliver Gaede would like to thank the GeoForschungsZentrum Potsdam for hosting him as a visiting researcher and the Queensland University of Technology for providing professional development leave.

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