AN INTEGRATED GEOMECHANICAL EVALUATION OF CAP AND FAULT-SEAL FOR RISKING PETROLEUM TRAP INTEGRITY USING DISTINCT ELEMENT AND BOUNDARY ELEMENT NUMERICAL METHODS

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ABSTRACT

This thesis comprises nine published papers on an integrated geomechanical evaluation of cap and fault-seal for risking petroleum trap integrity using distinct element and boundary element numerical methods. Paper 1 provides back-ground information and an introduction to the body of research presented in this thesis. In some parts of the Penola Trough, South Australia, the seal lithotype is fractured providing structural permeability and thereby compromising seal competency. This work inferred that existing geomechanical techniques, which only considered stresses on the fault plane, had limited application in the prediction of fracture generation within the country rock away from the well-bore. It also suggested that computational stress modelling techniques may provide a useful tool in this area and similar tectonic provinces.

An important stage of the modelling workflow is analysing the sensitivity of the numerical models to various input parameters. Papers 2 and 3 show that the models are particularly sensitive to fault parameters such as friction angle (ϕ) and cohesion (C). However, fault rock properties are not well understood in petroleum exploration due to depths of investigation and the expense of acquiring core samples.

This thesis develops a new technique, using widely available dipmeter data for the entire borehole. In this, rotations in borehole breakouts caused by discontinuities, in the vertical sense, are used to give qualitative indications of fault rock behaviour (Paper 3). These observations were used to make decisions about fault rock input parameters into the numerical stress models. Paper 8 showed the results of varying fault rock stiffness moduli

and fault zone width on the predicted stress within the surrounding rock mass. Where the prevailing stress conditions border between stress regimes, a new and unconventional technique whereby is used to increase confidence in understanding the stress regimes active at a particular depth and/or location (Paper 7). A comparative study of a single fault using three different methods of stress modelling, the distinct / discrete element (DEM), boundary element (BEM) and finite difference (FDM) methods (Paper 7) showed that the DEM underestimated the stress perturbation relative to the other models. Therefore where a clear variation is shown by DEM, there is increased confidence that it does exist and will be enhanced using other codes. Where there is the requirement to model multiple faults, DEM is preferred as the other methods trialled either have restrictions to the number of faults incorporated into the models (FDM) or does not account for full fault interaction and possible moment rotations between fault blocks, such as in the case of BEM.

The application of computational stress modelling offers a new workflow to fully integrate stress studies, cap-seal analysis, fault-seal analysis and structural interpretation to improve the understanding of hydrocarbon leakage risk at the prospect and play scales and was illustrated by way of multiple case study examples (Papers 4, 5, 6, 7 & 8).

The research presented in this thesis has development new concepts and additional workflows which add to the ‘tool-box’ that may be used by those researchers and consultants working in the field of petroleum geomechanics (Paper 9).

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1. DECLARATION

This work contains no material which has been accepted for the award of any other degree or diploma in any other university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Bronwyn Anne Camac

Papers offered for examination for the award of Doctor of Philosophy (Engineering Science) are as follows:

Paper 1:

Boult, P.J., **Camac, B.A.** and Davids, A.W. 2002. 3D Fault Modelling and Assessment of Top Seal Structural Permeability – Penola Trough, Onshore Otway Basin. *Australian Petroleum Production and Exploration Association Journal*, 42, 151 – 166

Paper 2:

Hunt, S. P., **Camac, B. A.** and Boult, P.J. 2003. A parametric analysis and applications of the Discrete Element Method for Stress modelling: *eNZ Conference Proceedings of the Rock Mechanics Association of Australia and New Zealand*.

Paper 3:

Camac, B. A., Hunt, S. P. and Boult, P.J. 2004. Fault and top seal integrity at relays and intersections using 3D Distinct Element Code. *Australian Petroleum Production and Exploration Association Journal*, 44, 481 - 496

Paper 4:

Camac, **B. A.,** Hunt, S. P. and Bailey, W. R. 2005. Distinct element stress modelling for top seal appraisal in the Pyrenees-Macedon oil and gas fields, Exmouth Sub-basin, Australian North West shelf. Alaska Rocks 2005, The 40th U.S. Symposium on Rock Mechanics (USRMS): Rock Mechanics for Energy, Mineral and Infrastructure Development in the Northern Regions, Anchorage, Alaska, June 25-29, 2005.

Paper 5:

Camac, B. A. and Hunt, S. P. 2004. Applications of Stress Field Modelling Using the Distinct Element Method for Petroleum Production: *APOGCE Conference Proceedings*, SPE Paper # 88473

<u>Paper 6:</u>

Camac, **B. A.,** Hunt, S. P and Boult, P. J. 2006. Local rotations in borehole breakouts – Observed and modelled stress field rotations and their implications for the petroleum industry. *International Journal of Geomechanics*, 6 (6) 399-410

<u>Paper 7:</u>

Camac, **B. A.,** Hunt, S. P., Boult, P. J. and Dillon, M. 2006. Unconventional borehole breakout rotation analysis provides a QC for stress models. *Australian Petroleum Production and Exploration Association Journal*, 46, 307-327

<u>Paper 8:</u>

Camac, B. A., Hunt, S. P. and Boult, P. J. 2009, Predicting brittle cap-seal failure of petroleum traps: An application of 2-D and 3-D distinct element method. *Petroleum Geoscience,* 15, 75-89

<u>Paper 9</u>:

Hunt, S.P., **Camac, B. A.** and Boult, P.J. 2006. A new geomechanical tool for the evaluation of hydrocarbon trap integrity. Golden Rocks 2006, The 41st U.S. Symposium on Rock Mechanics (USRMS): Rock Mechanics for Energy, Mineral and Infrastructure Development, Conference Proceedings

Other publications and/or presentations submitted during the course of the PhD but not offered up for examination:

Camac, **B. A.,** Hunt, S. P., Gilbert, C. E. and Anthony, D. P. 2005. Using 3D Distinct Element Method to predict stress distribution – Taranaki Basin, New Zealand. This extended abstract was prepared for presentation at the EAGE 67th Conference & Exhibition — Madrid, Spain, 13 - 16 June 2005. (Not Reviewed)

Boult, P. J., Lyon, P., **Camac, B. A.,** Edwards, D. and McKirdy, D. A. 2004. Subsurface plumbing of the Penola Trough: Otway Basin. *Eastern Australasian Basins Symposium (EABS) II Conference Proceedings*. **Fully Reviewed** Australian Conference Paper.

Hunt, S. P., Boult, P. J. and **Camac, B. A**. 2004. Discrete Element Stress Modelling in the Timor Sea and Otway Basin, Australia: EAGE Fault and Top Seals: What do we know and where do we go? Proceedings of the EAGE Conference, Montpellier, France. Paper-22 (Not Reviewed)

Dewhurst, D.N., Mildren, S. D., **Camac, B. A.,** Boult, P. J. and Hennig, A. 2003. Top Seal Fracturing in the Carnarvon and Otway Basins, Australia. AAPG International Conference & Exhibition September 21-24, 2003 • Barcelona, Spain – Poster Presentation (Not Reviewed)

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3. CONTEXTUAL STATEMENT

Previous research has shown the importance of understanding the relationship between fault geometry and current applied tectonic stresses in the prediction of critically stressed faults and their propensity for fluid flow via generated fracture networks along and/or around the fault plane. This thesis consisting of nine published papers attempts to increase this understanding, by applying the Distinct Element Method (DEM) to several case studies. For example, data collected from the Penola Trough, onshore Otway Basin, South Australia, shows that a more complex 3D failure mechanism may be active, whereby the cap-seal may fracture preferentially to fault failure (Paper 1).

In Paper 2, computational modelling techniques, using distinct / discrete element method (DEM) were applied to the problem of integrating cap and fault seal studies to determine a more comprehensive risking strategy for petroleum exploration. Paper 2 presents the results of a sensitivity study showing the effect of a single displacing fault on the applied regional stress. Input parameters such as the angle between the fault strike and the maximum horizontal stress direction (θ); the ratio of magnitudes of maximum and minimum stresses ($k= \sigma_1 / \sigma_3$); and friction angle ϕ were varied in this modelling experiment. This sensitivity study showed the models are highly sensitive to fault parameters, in particular the fault friction angle (ϕ).

Paper 3 addressed the importance of fault parameters by using dipmeter data to obtain borehole breakout information. Innovation involved plotting borehole break-out data with depth which was then used to identify possible fault intersections with the well-bore and observe rotations of regional stress trajectories. A rotation of the maximum principal horizontal stress perpendicular into the fault plane is indicative of a fault rock with a higher stiffness moduli than the surrounding rock mass. In the absence of rock strength data from laboratory tests, this technique offers a new procedure for making decisions about fault parameter inputs into numerical models.

The knowledge gained from the sensitivity studies and application of the new borehole break-out technique was applied in Papers 4, 5 and 6, to various case study examples within Australia and New Zealand. These case studies included the Penola Trough, (onshore Otway Basin); Pyrenees-Macedon fields, Exmouth Sub-basin (Northwest Shelf); Kupe Field, Taranaki Basin (New Zealand); Big Lake Field, Cooper Basin (South Australia); and the Jabiru-Tancred area, Timor Sea. In each of these studies DEM code was used in either two-dimensions (2-D UDEC) or three-dimensions (3-D 3DEC) and shows clear correlations between higher-than-regional predicted differential (2-D) or deviatoric stress (3-D) and brittle failure of the rock mass observed in petrophysical logs, core or from drilling information. Predicted mean and minimum stress from DEM models was also used to predict regions of preferred hydrocarbon pooling (Papers 6 and 7).

Paper 7 also offered a comparison of distinct / discrete element (DEM — 3DEC), finite difference (FDM — FLAC3D) and boundary element (BEM — MAP3D) methods for a single fault. In this comparative study, it was found that each of the methods gave similar results for a single fault. As a general trend, however, the BEM resulted in a larger perturbation effect, DEM indicated the least perturbation of differential stress, and the FDM yields a response that is of an intermediate order when compared to BEM and DEM. The differences were mostly attributable to variations in the way the fault geometry was treated in the three methods, that is, the specific discretisation scheme in each code; and the output gridding and display data created by the software. We know that the DEM method can account for multiple faults whereas there are restrictions with the FDM, and the BEM method does not account for full fault interaction and possible moment rotations between fault blocks, so where multiple fault interaction is required, the DEM is preferred.

Paper 8 explained an emerging application for DEM modelling, at the play and prospect level respectively, from the Penola Trough. Sensitivity studies at the prospect scale showed how (1) fault rock strength; (2) fault zone width; and (3) the interaction of two fault sets; generates local perturbations in the regional stress field. At the play-scale, the depth to which a younger active fault set propagates was explained by the distribution of stress within the rock mass generated by the present day far field stress acting on older regionally significant faults. This paper offered a workflow and highlighted the importance of understanding the effect of not only critically stressed and displacing faults but also that of fault rock that has higher cohesion, stiffness or frictional strength than the surrounding rock mass.

Finally, Paper 9 presented the results of the above research by way of a summary paper. This paper also gave an overview of three case studies presented in previous papers, the Penola Trough, Otway Basin, South Australia; Kupe Field, Taranaki Basin, New Zealand; and Pyrenees-Macedon fields, Northwest Shelf, Australia, highlighting the applicability and value of the developed techniques for the petroleum industry.