Improving the accuracy of vertical stress magnitude determinations in sedimentary basins

Matthew Musolino
The University of Adelaide
University of Adelaide
SA 5005
AUSTRALIA
matthew.musolino@ adelaide.edu.au

Rosalind King
The University of Adelaide
University of Adelaide
SA 5005
AUSTRALIA
rosalind.king@ adelaide.edu.au

Simon Holford
The University of Adelaide
University of Adelaide
SA 5005
AUSTRALIA
simon.holford@ adelaide.edu.au

Richard Hillis
The University of Adelaide
University of Adelaide
SA 5005
AUSTRALIA
richard.hillis@ adelaide.edu.au

SUMMARY

This study aims to highlight sources of uncertainty in the determination of vertical stress estimates using density log data and examines the compounding impacts of various workflows for calculating the vertical stress. To achieve this, we use petroleum data sets from the Moomba Gas field in the Cooper Basin, South Australia, Australia. The datasets encompass density, gamma and sonic 'check-shot' logs that enable stepwise analysis of overburden lithologies. The approach employed in this study helps to determine how the accuracy of vertical stress estimates can be influenced by (1), The calibration of sonic to density transforms; (2) Check-shot survey data and preparation (3) The application of contrasting methods for sonic-density transforms (e.g. the Gardner and Nafe-Drake methods) and (4) The use of filters to remove data in zones with poor borehole conditions (e.g. coals) and interpolation between voids in data. We find that the largest source of uncertainty in vertical stress determinations is the calibration of sonic to density transforms. These transforms are used to estimate the density of rock mass above which the density logging tools start recording. with the other factors contributing to uncertainty in decreasing magnitudes. Our analyses suggest that at 3 km (i.e. reservoir) depths, workflow and data processing decisions can introduce uncertainty in vertical stress magnitude determination equivalent to 3.5 MPa.

Keywords: stress, uncertainty, geomechanics,

INTRODUCTION

The vertical stress measurement is a key input for pore pressure prediction techniques and fractures gradient relationships (Matthews, 1967; Eaton, 1972; Tingay et al., 2009). Assumed vertical stresses of 1psi/ft by Dickinson (1953) can lead to erroneous predictions (Tingay et al., 2009b), translating indirectly to increased drilling costs, due to the increased number of casing points or fluid losses from accidental fracturing. (Tingay et al., 2009). The need for accurate measurements becomes even more important in regions where the magnitudes of principal stresses are similar, such as areas of overpressure (Zoback et al., 2003; Tingay et al., 2009) or where stress magnitudes vary over time due to fluid extraction, as observed in the North Sea (Teufel et al., 1991).

In the simplest sense, vertical stress at a point in the subsurface is calculated by integrating the density values above that point as a function of depth. The question of uncertainty arises due to the fact that wells are rarely logged by the density tool from the surface throughout the drilled sections, and thus in parts of the well, densities are indirectly estimated. Additionally, various borehole conditions affect the reliability of density estimates. Communication of vertical stress estimation workflows appears in most relevant work with varying degrees of explanation. Some authors give a brief statement of where the vertical stress data is from, i.e. 'overburden weight', or simply set this at 1psi/ft. Others provide a step-by-step explanation or in-depth analysis (Hasegawa et al., 1985; Suchowerska et al., 2013; Bredehoeft et al., 1976; Zoback & Healy, 1992; King et al., 2008; Nelson & Hillis, 2005; Tingay et al., 2003). However, even when workflows for vertical stress determination are relatively detailed, there is often little attention paid to the uncertainties that are introduced due to the treatment of the data. For example, whilst some authors give explanations of the use of de-spike filters and calibration of sonic density transforms (Tingay, 2003; Nelson & Hillis, 2005), in many cases, there is no consistent referenced method of vertical stress calculation. Many studies do not provide a fully resolved explanation of the tangible changes how approaches to the filtering of density data, the reintegration of filtered material, the smoothing of data or sonic density calibration, and how these may affect the accuracy of vertical stress determinations. One example is the DRHO value which is the density correction value reported when the tool takes a reading. Various values between 0.05-0.2 g/cm^3 are used. Similarly, the bit size to borehole size values has cut off ranges between 5 and 10%, though these are often arbitrarily applied.

This study examines how varying workflows affect uncertainties in vertical stress determination in a relatively well-constrained geological setting. We focused on the Moomba 61well in the Moomba Gas field in the Cooper Basin. The well was chosen due to it having one of the more robust data sets in basin, the wireline logs provided density, gamma, sonic and electrical logs detailing large sections of borehole. Critically, the well also had a check-shot survey taken directly on its location. For regional calibration of the density sonic transforms we took eight wells within 20 km of the focus well in the South West Nappamerri Trough.

The main findings of this study are **1**. Differences in vertical stress magnitude estimates are demonstrated by simple workflow decisions and are observable at reservoir level depths. **2**. Using available regional data helps to improve stress magnitude estimation by better calibrating lab derived sonic density transforms to specific regions. **3**. New principles can be applied in the preparation of data that better incorporate the available geological information. This includes a new technique for integrating low-density coal units back into density logs and, recommendations of using the standard Gardner transform when no calibration to the regions density/sonic trend. the Nafe-Drake is recommended when regional data sonic/density trends are available for calibration.

METHOD AND RESULTS

The following are the four major vertical stress workflow tasks investigated in this study.

1. **Calibrating Nafe-Drake / Gardner equations**
2. **Check-shot survey preparation and evaluation**
3. **Comparing Nafe-Drake / Gardner equations**
4. **Filling gaps in density log data from filtering**

1. As previously mentioned, due to borehole conditions (primarily rugosity), density data and their equivalent depth sonic data must be filtered out of the data set. It is thought that that outside the bounds of the filter, the data is not reliable. Density and velocity data from eight wells in the South West Nappamerri Trough are filtered by three different filters (**Filter 1** = 0.2 DRHO & 10% bit size, **Filter 2** = 0.1 DRHO & 7.5% bit size and **Filter 3** = 0.05 DRHO and 5% bit size). The data is cross-plotted using the average density and sonic point to calibrate the Gardner (1974) and Ludwig et al., (1970) (Nafe-Drake) sonic density transforms. Tighter filters result in higher average velocity/density values. **FIGURE 1** Shows the shift of both sonic densities transforms when using velocity/density values from **Filter 3 (dotted line to solid line).** When Filter 3 is applied, The Nafe-Drake transform requires calibration of +0.0796 g/cm^3 to match the density sonic trend seen in this section of the Cooper Basin. The Gardner transform only required a 0.0029 g/cm^3 shift. It appears the rocks that make up the Nappamerri Trough are closer in density sonic characteristic to the original data set by Gardner. This applies to the density/sonic velocity range between 2-2.8 g/cm^3 and 3.6-5.9 km/s.

2. The calibrated equations allow density to be derived from one-way travel time values from check-shot surveys. This allows for the estimation of rock mass average density between the surface and the start of the density tool data readings. Using existing check-shots as a proxy for multiple wells without check-shots is an established practice, and we explore the effects of this practice. Firstly, we assess the effect that the geometry of check-shot surveys has on the subsequent stress magnitudes derived from its use. check-shot surveys are referenced to a seismic reference datum. Therefore, there is a distance between the surface and seismic reference datum. A velocity estimate and subsequence density value must be added to the surveys values to integrate all densities to the surface. Our study compares the check-shot surveys completed for two wells located 6 km apart and which drilled through reasonably homogenous geology; the Moomba 61 and Moomba 60 gas wells. There is 35 m between the surface and seismic reference datum in the case of Moomba 61 and, in the case of Moomba 60, 41m. The estimated travel time by the survey providers over that 35m (given the name 'surface to datum static') when converted to density and integrated to stress accumulation, accounts for 0.54-0.64 MPa (Nafe-Drake – Gardner) of stress accumulation. For Moomba 60 this is 0.57-0.72 MPa (Nafe-Drake – Gardner). Secondly, we compare stress estimates between the two check-shot surveys below the seismic reference datum. At 2696 m (above which depth no density data is available and a velocity to density transform is required) the stress estimate using velocities from the Moomba 61 check-shot was 59.47-59.54 MPa (Nafe-Drake-Gardner) and 58.98-59.16 MPa (Nafe-Drake-Gardner) using the Moomba 60 check-shot velocities). This is a difference of 0.49-0.38 MPa.

3. We compare how accurately the Nafe-Drake/Gardner transforms predict density where we have an uninterrupted section of density data. Between 2967- 2994m the average density is 2.586 g/cm^3 given by the density tool (**TABLE 1**). Both the Gardner and Nafe-Drake transforms underpredict the density, 2.428 and 2.359 g/cm^3 respectively. After calibration **(Figure 1),** the Gardner and Nafe-Drake transforms perform better 2.431 and 2.438 g/cm^3 respectively.

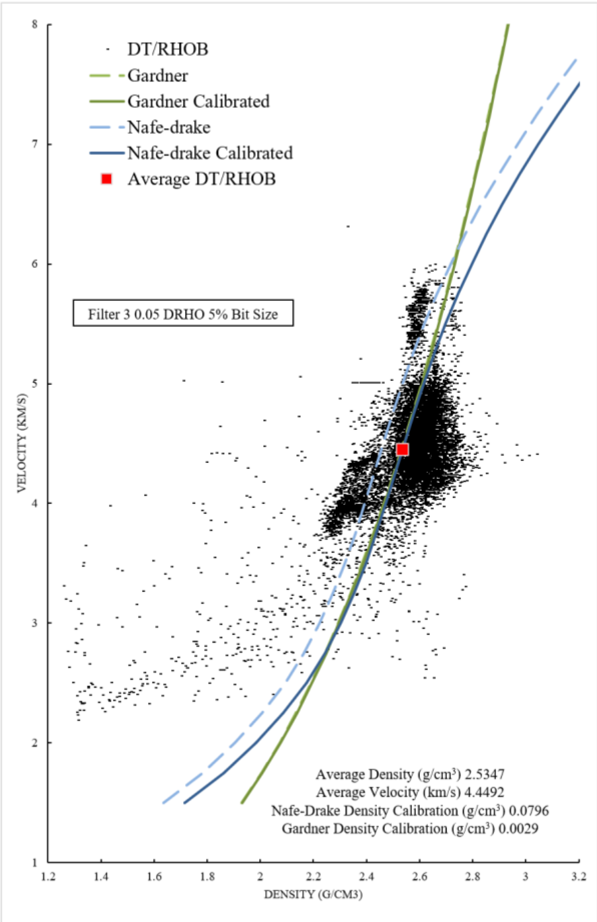

FIGURE 1. Cooper Basin regional velocity/density data filtered by 0.05 DRHO and 5% bit size. Overlayed are the Gardner and Nafe-Drake density sonic transforms and their calibration to the regional density/velocity average.

4. Filtering the density log due to poor borehole conditions creates gaps that need to be filled with reasonable density estimates. The Cooper Basin hosts coal beds that are disproportionately filtered out of data due to their effect on borehole conditions. We have developed a new approach for better estimating density and thus stress magnitude in well sections that contain coals, using the approach highlighted in

CONCLUSIONS

The objective of this study is to better explore and communicate the uncertainty in vertical stress estimates. This research allows us to provide the following conclusions and recommendations pertaining to the methodology of in-situ stress calculations. The work provides insight into the potential magnitudes of vertical stress uncertainty at reservoir depths in the Cooper Basin.

1. In general, the Gardner (1974) sonic velocity to density transform should be used for the Cooper Basin if no calibration to the regional density/velocity trend is attempted. If regional density/velocity trend is available and both the Gardner and Nafe-Drake transforms are calibrated to that trend, then the Nafe-Drake transform will better predict density for most lithologies in the South West Nappamerri Trough in the Cooper Basin. Additionally, using a tighter filter for this calibration is advantageous as it removes a lot of spurious data.

2. The practice of using check-shot surveys as a velocity proxy from nearby wells highlights **1**. The importance of incorporating a 'surface to datum static' measurement for integration, not doing so may underpredict stress depending on depth difference between a seismic reference datum and the surface. in our case 0.54 MPa (ND) for a 35m difference using Moomba 61 as an example. **2**. In this best-case scenario where the wells are close together (6km) in an area of geological homogeneity, there is still observable velocity differences resulting in stress estimates at 2696m of 0.49 MPa (ND).

3. The Nafe-Drake transform once calibrated shows to be more accurate than the Gardner at predicting density from check-shot data at reservoir depths in the study area (i.e. >2.7 km).

4. We have developed a method that incorporates geological knowledge into estimations of density between voids created

by data filtering and reintroduction of disproportionately filtered coal units.

Our findings show that ~3km depth in the Moomba Gas field, the uncertainty in vertical stress magnitude may be up to 3.5 MPa depending on the decisions made during wireline log analysis/geomechanical workflows. Whilst this degree of uncertainty may seem minor, improved knowledge of the sources of these uncertainties is critical for wellbore stability and hydraulic fracturing efforts in the Cooper Basin.

ACKNOWLEDGMENTS

The Authors would like to thank the ASEG (Australian Society of Exploration Geophysicists) Research Foundation for supplying funding for this research.

REFERENCES

Bredehoeft, J., Wolff, R., Keys, W., and Shuter, E., 1976, Hydraulic Fracturing to Determine the Regional in Situ Stress Field, Piceance Basin, Colorado. *Geological Society of America Bulletin* **87**, 250-58.

Dickinson, G., 1953, Geological Aspects of Abnormal Reservoir Pressures in Gulf Coast Louisiana. *AAPG Bulletin* **37**, 410-32

Eaton, B.A., 1976, Graphical Method Predicts Geopressures Worldwide. *World Oil;(United States)* **183**.

Gardner, G., Gardner, L., and Gregory, A., 1974, Formation Velocity and Density—the Diagnostic Basics for Stratigraphic Traps. *Geophysics* **39**, 770-80.

Hasegawa, H.S., Adams, J., and Yamazaki, K., 1985, Upper Crustal Stresses and Vertical Stress Migration in Eastern Canada. *Journal of Geophysical Research: Solid Earth* **90**, 3637-48.

King, R.C., Hillis, R.R., and Reynolds, S.D., 2008, In Situ Stresses and Natural Fractures in the Northern Perth Basin, Australia. *Australian Journal of Earth Sciences* **55**, 685-701.

Ludwig, W., Nafe, J., and Drake, C., 1970, The Sea, Vol. 4, Part 1. Wiley-Interscience London.

Matthews, W., 1967, How to Predict Formation Pressure and Fracture Gradient from Electric and Sonic Logs. *Oil and Gas*.

Nelson, E. and Hillis, R., 2005, In Situ Stresses of the West Tuna Area, Gippsland Basin. *Australian Journal of Earth Sciences* **52**, 299-313.

Suchowerska, A., Merifield, R.S., and Carter, J.P., 2013, Vertical Stress Changes in Multi-Seam Mining under Supercritical Longwall Panels. *International Journal of Rock Mechanics and Mining Sciences* **61**, 306-20.

Teufel, L.W., Rhett, D.W., and Farrell, H.E., 1991, Effect of Reservoir Depletion and Pore Pressure Drawdown on in Situ Stress and Deformation in the Ekofisk Field, North Sea. *The 32nd US Symposium on Rock Mechanics (USRMS)*.

Tingay **(B)**, M.R., Hillis, R.R., Swarbrick, R.E., Morley, C.K., and Damit, A.R., 2009, Origin of Overpressure and Pore-Pressure Prediction in the Baram Province, Brunei. *Aapg Bulletin* **93**, 51-74.

Tingay, M., Hillis, R., Morley, C., Swarbrick, R., and Okpere, E., 2003, Variation in Vertical Stress in the Baram Basin, Brunei: Tectonic and Geomechanical Implications. *Marine and Petroleum Geology* **20**, 1201-12.

Tingay, M.R., Hillis, R.R., Morley, C.K., King, R.C., Swarbrick, R.E., and Damit, A.R., 2009, Present-Day Stress and Neotectonics of Brunei: Implications for Petroleum Exploration and Production. *AAPG Bulletin* **93**, 75-100.

Zoback, M., Barton, C., Brudy, M., Castillo, D., Finkbeiner, T., Grollimund, B., Moos, D., Peska, P., Ward, C., and Wiprut, D., 2003, Determination of Stress Orientation and Magnitude in Deep Wells. *International Journal of Rock Mechanics and Mining Sciences* **40**, 1049-76.

Zoback, M.D. and Healy, J.H., 1992, In Situ Stress Measurements to 3.5 Km Depth in the Cajon Pass Scientific Research Borehole: Implications for the Mechanics of Crustal Faulting. *Journal of Geophysical Research: Solid*

TABLE 1. Table shows average densities and stress accumulation for two intervals. Firstly, a small interval of uninterrupted good quality density data between 2967and 2994m and secondly the entire density log section filtered and prepared as per FIGURE 3. This is then compared to the Gardner and Nafe-Drake transforms over that same depth from C-S (Check-Shot) data from the same well.

Measure	Filter 1 (Log Density)	Filter 3 (Log Density)	Gardner (C-S. Rhob)	Gardner (Calibrated C-S. Rhob)	Nafe-Drake (C-S. Rhob)	Nafe-Drake (Calibrated C-S. Rhob)
Average density (g/cm^3) 2967-2994m	-	2.586	2.428398506	2.431	2.358	2.438
Stress accumulation (MPa) 2967-2994m	-	0.680	0.6424	0.643	0.624	0.645
Average density (g/cm^3) 2696-3252m	2.545*	2.488397*	2.437	2.440881	2.362	2.442
Stress accumulation (MPa) 2696- 3252m	13.890	13.828	13.360	13.37632	12.954	13.388

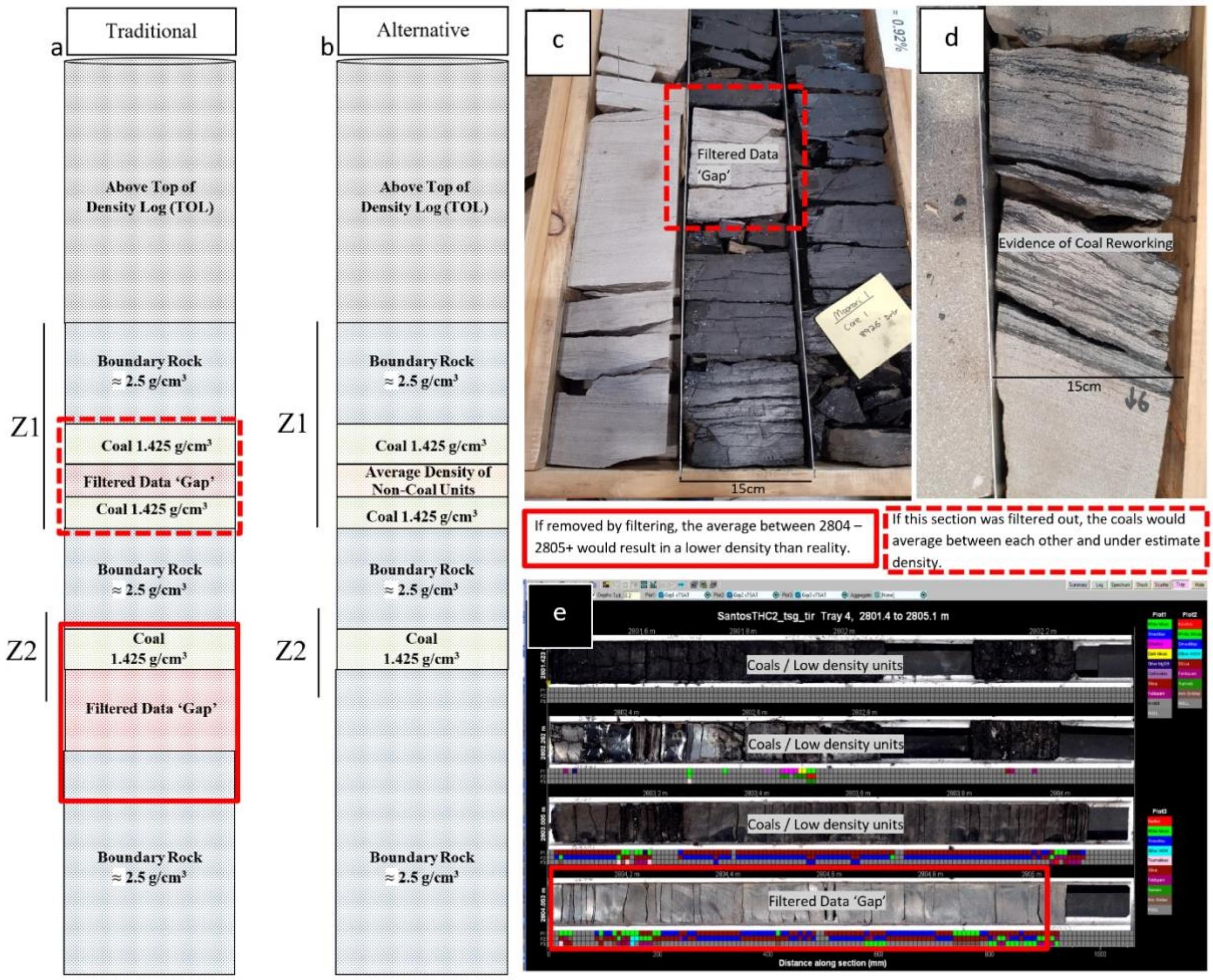

FIGURE 2. (a) diagram shows a stylised lithology log. Under 'Traditional' The shaded red denotes a gap in data created by the filter used. In section 'Z1' the broken line box demonstrates how averaging between two coal bodies would result in a lower density estimate. Core log from the Cooper Basin (c) shows what this could look like in reality. Additionally, the unbroken red box in Z2 shows how averaging between coal and the boundary rock would produce lower density estimates when it's possible that the section may look like the section indicated in the unbroken dox indicated (e). The alternative method (b) gives a more realistic density estimate by filling the gap in coal (Z1) with an average of non-coal density and bringing the boundary rock up to meet the coal in Z2.