Understanding present-day stress in the onshore Canning Basin of Western Australia

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ABSTRACT

Western Australia’s Canning Basin is an underexplored prospective basin with proven petroleum systems and small-scale production. Recently, several formations within deeper depocentres have been investigated for unconventional hydrocarbon resources. Modern petroleum resource evaluation generally depends on an understanding of local and regional stresses that are a primary control over the formation and propagation of induced fractures. There are significant gaps in our understanding of these factors within the Canning Basin. This study characterises the regional stress regime of the onshore Canning Basin and presents modelled present-day stress, allowing for the identification of significant stress heterogeneity and natural fracture barriers. Interpretation of wireline data reveals a present-day state of stress with variation in magnitude and faulting-type. An approximately north-east–southwest regional present-day maximum horizontal stress orientation is interpreted, which is in broad agreement with the Australian Stress Map and previously published data. One-dimensional mechanical earth models, constructed for intervals from 15 Canning Basin wells, highlight the relationship between lithology and stress. Significant changes in stress within and between lithological units, owing to the existence of discrete mechanical units forming numerous inter- and intra-formational stress boundaries, likely to act as natural barriers to fracture propagation, particularly within those units currently targeted for their unconventional resource potential, are interpreted. A strike-slip faulting stress regime is interpreted broadly through the basin. However, when analysed in detail there are three distinct stress zones identified: (1) a transitional reverse- to strike-slip faulting stress regime in the top ~1 km, (2) a strike-slip faulting stress regime from ~1 km to ~3.0 km and (3) a transitional strike-slip to normal faulting regime at depths greater than ~3.0 km. This study is a component of the Australian Government’s Exploring for the Future initiative, which focusses on gathering new data and information about northern Australia’s resource potential.

KEY POINTS

1. New stress data, including 15 mechanical earth models, are presented for Western Australia’s onshore Canning Basin.
2. Broadly, a strike-slip stress regime with a NE–SW-oriented maximum horizontal orientation is described.
3. Significant stress heterogeneities and natural fracture barriers are identified.

Introduction

Exploring for the Future (EFTF) is a 4-year initiative by the Australian Government focused on gathering new data and information about the potential mineral, energy and groundwater resources concealed beneath the surface across northern Australia (Blewett, 2017). This area is generally underexplored in comparison with southern Australia, and offers enormous potential for industry development. While under-developed, northern Australia is advantageously located close to major global markets and infrastructure and hosts many prospective regions. One aim of the EFTF program is to improve the understanding of the petroleum resource potential of northern Australia, building upon current understanding of regional petroleum systems in order to drive new investment in the region.

The Lower Ordovician to Lower Cretaceous Canning Basin (Figure 1) is one of northern Australia’s most prospective onshore petroleum basins, with proven petroleum systems and current production from conventional reservoirs (Ghori, 2013; Hashimoto et al., 2018). Following the discovery of gas at the well Yulleroo 1 in 1967, rising oil prices in the 1970s and 1980s led to a significant phase of exploration in the basin. While further exploration and discoveries of both oil and gas
followed, including at the Blina, Sundown and Ungani fields (Crostella, 1998; D’Ercole et al., 2003; Ghori, 2013), the Canning Basin is still yet to become a major hydrocarbon producing province (Hashimoto et al., 2018, and references therein). Buru Energy are currently producing conventional oil from the Ungani oil field and are primarily pursuing conventional oil and gas targets. However, much of the recent exploration interest has been for unconventional hydrocarbons within the deeper basin depocentres. Buru Energy, with partners Mitsubishi Corporation and Rey Resources Limited, drilled several wells in the 2010s, targeting a basin-centred gas play within the Lower Carboniferous Laurel Formation (Hashimoto et al., 2018). New Standard Energy and Finder Exploration targeted potential shale gas resources within the Ordovician Goldwyer Formation. Theia Energy are currently pursuing the lower Goldwyer liquids-rich play on the Broome Platform following oil and gas shows and indications of overpressure at the well Theia 1 (D’Ercole et al., 2003; Hashimoto et al., 2018) (Figure 2).

Despite ongoing exploration, the Canning Basin is one of the least explored Paleozoic basins in the world (Carr et al., 2020). Seismic data and wells drilled are limited
largely to the northern part of the basin (Figure 1) (Hashimoto et al., 2018).

The Kidson Sub-basin, a significant depocentre in the southern Canning Basin, covers an area of $\sim 91,000 \text{ km}^2$ (Figure 1). It is largely unexplored with no well penetration and is one of the primary study areas for the EFTF Energy program (Carr et al., 2020). Extensive work has now been undertaken to address the lack of seismic data and to
increase the resource prospectivity of the region (Carr et al., 2020). Geoscience Australia recently acquired the L211 deep crustal seismic reflection survey, imaging an approximately 6.4 km deep sedimentary basin, containing a lower conformable package of Cambrian to Devonian clastic sediments, carbonates and evaporates (Southby et al., 2020). This new dataset implies that several identified conventional and unconventional petroleum systems are likely to extend from the northern Canning Basin and into the Kidson Sub-basin (Carr et al., 2020; Southby et al., 2020).

Hydrocarbon extraction from low permeability reservoirs, such as the shales and tight sandstones of the Canning Basin, requires hydraulic stimulation to create permeability pathways that enable the flow of fluid from the reservoir to the well (Bell, 1990; Bell & Babcock, 1986). Local and regional tectonic stresses act as a primary control over the generation and propagation of hydraulic fractures; thus, an understanding of present-day stresses has become increasingly important to modern petroleum exploration and production (Bell, 1996a; 2003; Hillis & Reynolds, 2003; Zoback, 2007). In most cases, tensile hydraulic fractures will form perpendicular to the minimum stress direction, as this is the path of least resistance for fracture formation. Therefore, understanding present-day stress orientations and magnitudes is critical for predicting the initiation and propagation of hydraulic fractures associated with reservoir stimulation, and also has implications for borehole stability, well and water-flood design, and fault reactivation (Addis et al., 1993; Caillet, 1993; Hillis & Reynolds, 2003; Hillis & Williams, 1993a, 1993b; Horn, 1991; Mildren et al., 1994).

Present-day stress is defined by the relative orientation and magnitude of three mutually orthogonal principal stresses, defined as orientations where only normal stresses exist, specifically a maximum ($\sigma_1$), minimum ($\sigma_3$) and intermediate ($\sigma_2$). Owing to the fact that the earth’s surface is a free surface, unable to support shear stresses and the mass of the overburden, one of these stresses is generally vertical and is known as $\sigma_w$, constraining the two remaining stresses to the horizontal plane (Anderson, 1951; Bell, 1996a; Sibson, 1977; Zoback, 2007). These are referred to as the maximum ($\sigma_1$) and minimum ($\sigma_3$) horizontal stresses (Bell, 1996a) (Figure 3). Where one stress is assumed to be vertical, knowledge of either horizontal stress orientations ($\sigma_{H1}$ or $\sigma_{H2}$) enables the orientations of all three stresses to be determined (Bell, 1996a; Tingay et al., 2003). The relative magnitudes of the three principal stresses define a stress regime (Anderson, 1951) (Figure 3); under any given stress regime, the type of failure defined will typically dominate (Heidbach & Höhne, 2008; Sibson, 1977). For further information regarding the definition of lithospheric stresses, see Bell (1990), Bell (1996a, 1996b), Bell (2003), Chan et al. (2014), Couzens-Schultz and Chan (2010), Plumb et al. (2000) and Zoback (2007).

The Australian stress field is noted as being highly variable, with continent-wide stress patterns that are not oriented subparallel to absolute plate motion as they are in many other continents, instead featuring significant rotations of stress orientation on a regional scale (Hillis & Reynolds, 2000, 2003; Rajabi, Tingay, Heidbach, et al., 2017; Rajabi, Tingay, King, et al., 2017; Rajabi et al., 2016; Richardson, 1992; Zoback & Zoback, 1989).

There have been numerous studies analysing the origin and state of continental Australia’s crustal stress pattern from a broad range of perspectives. A summary is presented by Rajabi, Tingay, Heidbach, et al. (2017), who use the most up-to-date Australian stress database to generate and model continent-scale stresses throughout Australia. Rajabi, Tingay, Heidbach, et al. (2017) also note that while the large-scale driving mechanisms of plate tectonics are the main sources of intraplate stress in the Australian continental crust, geological features such as faults, fractures, lithological density, strength contrasts and intraplate volcanism result in extensive localised stress perturbations in the studied basins. Additionally, Rajabi, Tingay, Heidbach, et al. (2017) highlight that although stress orientations are determined in more detail than stress magnitudes or regimes, the compiled stress data in the Australian Stress Map indicates that shallower parts of the Australian crust are primarily characterised by a present-day thrust faulting stress regime that changes to a prevailing strike-slip stress regime at greater depths.

Although it forms one of the initial 16 stress provinces defined in the Australian Stress Map (Hillis et al., 1998; Hills & Reynolds, 2000, 2003), limited stress data are available over the Canning Basin (Bailey & Henson, 2018, 2019; Rajabi, Tingay, Heidbach, et al., 2017). The Australian Stress Map project currently includes the Canning Basin as one of 30 defined stress provinces for continental Australia and...
A stress province is defined as a close geographic region (typically a basin) where at least four $\sigma_v$ orientation records of suitable quality exist (Hillis et al., 1998; Hillis & Reynolds, 2000, 2003; Rajabi, Tingay, Heidbach, et al., 2017). Bailey and Henson (2019) undertook a detailed interpretation of $\sigma_v$ magnitudes in the Canning, noting that the basin is broadly subject to a strike-slip faulting stress regime that varies based on lithology (Bailey & Henson, 2018) and hosts highly variable $\sigma_v$ magnitudes. Bailey and Henson (2018) constructed several one-dimensional mechanical earth models (1D MEMs) to quantify stress magnitudes. This study builds upon the work of Bailey and Henson (2018) and presents modelling of additional calibration data, further developing our understanding of the present-day stress field in the onshore Canning Basin.

The aim of this study was to characterise the regional stress regime within the onshore Canning Basin and to build detailed models of stress magnitude within the subsurface, allowing for the identification of significant stress heterogeneity, hence, isolating natural barriers to fracture propagation. Data from 22 petroleum and stratigraphic borehole failure features observed in wellbore image logs. The resulting models and interpretations, included in this study, provide insight into the present-day stresses of the onshore Canning Basin of Western Australia and provide broad constraints for exploration of sediments within the highly prospective Kidson Sub-basin.

Geological setting

The Lower Ordovician to Lower Cretaceous Canning Basin is a polyphase, intracratonic to passive margin sedimentary basin covering approximately 430 000 km$^2$ across Western Australia (Figure 1). The basin is dominated by two large northwest–southeast-trending depocentres: the ~15 km thick Fitzroy Trough–Gregory Sub-basin complex and the ~6.4 km thick Willara Sub-basin–Kidson Sub-basin complex (Kennard, 1994; Southby et al., 2020; Towner & Gibson, 1983) (Figures 1 and 4). Both depocentres are filled with a Lower Ordovician to Lower Cretaceous sedimentary succession (Figure 2), and are flanked by several fault-bounded terraces and shelves, and separated by a mid-basin arch composed of the Broome and Crossland platforms (Hashimoto et al., 2018; Kennard, 1994) (Figures 1 and 4). The sedimentary succession was generally considered to be thinner and less deformed in the southern areas of the basin (Department of Mines & Petroleum, 2014, 2017); however, deep crustal seismic data recently acquired by Geoscience Australia indicate that sediment thickness in the Kidson Sub-basin reaches up to 6.4 km (Southby et al., 2020) (Figure 4). The basin is bounded and underlain to the north by the Precambrian Kimberley Block, whereas in the east the Canning Basin succession interfingers with the
Neoproterozoic–Upper Devonian Amadeus Basin and is bounded and underlain by the Mesoproterozoic Musgrave Province and the Paleoproterozoic Warumpi Province. The Paleoproterozoic–Neoproterozoic Paterson Orogen, the Neoproterozoic–lower Paleozoic Officer Basin and the Archean Pilbara Craton define the southern boundary of the Canning Basin. Offshore to the west, the Canning Basin adjoins the Carboniferous–Cenozoic Roeubuck and Browse basins (Hashimoto et al., 2018).

The Canning Basin initiated as an intracratonic rift and sag basin during the Early Ordovician (Figure 2), with shallow marine to marginal conditions present across much of central and northern Australia. Individual depocentres developed as marine to marginal environments, including fluvial, evaporitic, eolian, fluviodeltaic, paralic, carbonate reef and marine shelf.

The Canning Basin has a complex history involving several major tectonic phases of extension, thermal subsidence, transpression and inversion (Figure 2) (Department of Mines & Petroleum, 2014; Hashimoto et al., 2018; Kennard, 1994; Nicoll et al., 1994; Totterdell et al., 2014; Towner & Gibson, 1983; Veevers, 1976). The Middle–Late Triassic is acknowledged as the major period of deposition in the onshore basin (Figure 2) and minor cover deposition occurred during the Jurassic–Early Cretaceous (Department of Mines & Petroleum, 2014).

Deposition occurred in a range of marine and non-marine environments, including fluvial, evaporitic, eolian, fluviodeltaic, paralic, carbonate reef and marine shelf.

The Canning Basin has a complex history involving several major tectonic phases of extension, thermal subsidence, transpression and inversion (Figure 2) (Department of Mines & Petroleum, 2014; Hashimoto et al., 2018; Parra-Garcia et al., 2014; Romine et al., 1994; Shaw et al., 1995):

1. Early Ordovician–Silurian extension and subsidence (Samphire Marsh Movement);
2. Late Silurian–Early Devonian uplift and erosion (Prices Creek Movement);
3. Devonian–Early Carboniferous extension and subsidence (Pillara Extensional Movement);
4. Middle–Late Carboniferous transpression, uplift and erosion (Meda Transpressional Movement);
5. Late Carboniferous–Triassic extension and subsidence (Point Moody Extensional Movement); and
6. Early Jurassic transpression, uplift and erosion (Fitzroy Transpressional Movement).

Kennard (1994) and Romine et al. (1994) established a sequence stratigraphic framework for the Canning Basin based on these tectonic events. Haines (2009) modernised the framework, and detailed descriptions of each event can be found in Hashimoto et al. (2018) and Figure 2.

Modelling present-day stresses

Data sources and data quality

Data used in this study, including well tests, well-logs, well completion reports and associated data, were exclusively from open-file petroleum and stratigraphic wells sourced from the Western Australian Petroleum and Geothermal Information Management System (WAPIMS). Data were evaluated for quality and reliability, processed to remove erroneous values and compiled for use. Further data-cleansing processes were applied as required and calculations and these are specified where relevant.

Characterising the present-day stress state of the Canning Basin requires the determination of both orientation and magnitude of the three principal stresses, $\sigma_h$, $\sigma_v$, and $\sigma_t$. Image log data from 15 wells were used to determine the orientation of $\sigma_h$ and $\sigma_t$, $\sigma_v$ magnitudes were sourced from Bailey and Henson (2019). The magnitudes of $\sigma_h$ and $\sigma_t$ were determined through the construction of 1D MEMs for 16 wells across the Canning Basin (after Bailey & Henson, 2018) (Table 1).

Vertical stress magnitude

It is generally assumed that one of the principal stresses is vertical (Figure 3), given that the earth’s surface is a free boundary and the stress caused by gravity acting on a weight of material is directed downwards (Schmitt et al., 2012). This vertical, or overburden, stress ($\sigma_v$) is controlled by the mass of overburden present over a given depth, and is generally calculated through an integration of bulk rock density (Bell, 1996a). Where no overlying water column is present, such as in the onshore Canning Basin, the following equation applies:

$$\sigma_v = \int_0^z \rho(z) g \, dz$$  \hspace{1cm} (1)

Where $\rho(z)$ is overburden density at depth $z$, and $g$ is gravitational acceleration (Bell, 1996a; Engelder, 2014; King

| Well          | Image log | 1D MEM | BO modelled | Latitude | Longitude |
|---------------|-----------|--------|-------------|----------|-----------|
| Asgard 1      | No        | Yes    | Yes         | –18.25   | 125.03    |
| Commodore 1   | –         | Yes    | –           | –19.19   | 122.44    |
| Cyrene 1      | –         | Yes    | –           | –18.28   | 122.40    |
| Fruitcake 1   | –         | Yes    | –           | –19.47   | 124.48    |
| Nicoy 1       | FMI       | Yes    | –           | –20.57   | 123.26    |
| Paradise 1    | Deepening | –      | Yes         | –18.00   | 124.58    |
| Pictor East 1 | XRMI      | Yes    | –           | –18.77   | 123.73    |
| Praslin 1     | CMI       | –      | No          | –17.98   | 123.02    |
| Robert 1      | –         | Yes    | –           | –19.16   | 124.33    |
| Senagi 1      | CMI       | –      | No          | –18.59   | 124.37    |
| Sunbeam 1     | –         | Yes    | –           | –17.54   | 124.37    |
| Theia 1       | CMI       | Yes    | –           | –18.90   | 123.29    |
| Ungani 2      | XRMI      | –      | –           | –17.99   | 123.16    |
| Ungani 3      | CBIL      | –      | Yes         | –17.99   | 123.17    |
| Ungani Far West 1 | CMI | –      | No          | –18.00   | 123.13    |
| Ungani North 1 | FMI   | Yes    | –           | –17.93   | 123.16    |
| Valhalla 2    | EMI       | Yes    | –           | –18.07   | 124.77    |
| Valentine 1   | FMI       | –      | No          | –17.14   | 123.71    |
| Victory 1     | UMI       | –      | No          | –18.25   | 123.93    |
| Yulleroo 2    | –         | Yes    | –           | –17.86   | 122.93    |
| Yulleroo 3    | FMI       | Yes    | –           | –17.85   | 122.89    |
| Yulleroo 4    | FMI       | Yes    | –           | –17.82   | 122.88    |

Wells were selected on the basis of hosting either image log data or shear and compressional sonic logs for the creation of 1D MEMs. All well data used were open-file and were acquired via the Western Australian Petroleum and Geothermal Information Management System (WAPIMS).
The density logs used to calculate $\sigma_v$ are not always run to surface so are, where unavailable, estimated using the empirically derived Gardner (Gardner et al., 1974) velocity-density transform, to estimate a top-of-log stress value from well velocity survey data and allow a vertical stress profile to be constructed (King et al., 2010; Tingay et al., 2003; Zoback, 2007). Bailey and Henson (2019) used wellbore data from 102 open-file petroleum wells to characterise vertical stress within the onshore Canning Basin, interpreting $\sigma_v$ magnitudes from density logs and checkshot data. The authors calibrated the Gardner velocity-density transform to Canning Basin stratigraphy, taking into account the complexities of variable lithology within each well (Bailey & Henson, 2019). Interpreted $\sigma_v$ magnitudes at 1 km depth below the ground surface range from 20.5 to 25.0 MPa km$^{-1}$ with a mean value of 22.1 MPa km$^{-1}$ (SD = 1.0 MPa km$^{-1}$) (Figure 5). The authors note significant variation within the calculated stress magnitudes and identify three regions of elevated $\sigma_v$ magnitude: the Barbwire Terrace, the Devonian reef complexes of the northern Lennard Shelf, and the Mowla Terrace (Figure 5). Potential mechanisms for the observed variation were investigated; including abnormal pore pressures, tectonic uplift and lithology. Although abnormal pore pressures are identified, these are interpreted as being the result of disequilibrium compaction or fluid expansion mechanisms, neither of which can result in elevated $\sigma_v$ magnitude. Significant disequilibrium compaction results in porosity preservation and, therefore, lower than expected density values. Vertical stress profiles in wells featuring interpreted disequilibrium compaction overpressure have vertical stress gradients that indicate little or no decrease in $\sigma_v$ owing to porosity preservation (Bailey & Henson, 2019). The Canning Basin’s extensive uplift history is suggested as a potential mechanism for elevated $\sigma_v$ magnitudes (Bailey & Henson, 2019). Bailey and Henson (2019) suggested that while uplift is likely to exert some influence over $\sigma_v$ magnitudes in the Canning Basin, the primary reason for significant variations in $\sigma_v$ is lithological; that is, areas of elevated $\sigma_v$ magnitude are also areas where thick intervals of carbonate sediments are present.

**Horizontal stress orientations**

Horizontal stress orientations can commonly be identified from wellbore-failure features within drill holes (Bell, 1996a). Two main wellbore-failure features are commonly...
used as stress indicators: borehole breakthroughs (BOs) and drilling induced tensile fractures (DITFs) (Figure 6). As rock is removed during drilling, stress is concentrated around the wellbore; circumferential stress is maximised at the minimum horizontal stress azimuth and minimised at the maximum horizontal stress azimuth (Gough & Bell, 1981; Haimson & Herrick, 1986; Maloney & Kaiser, 1989; Zheng et al., 1989; Zoback et al., 1985). Borehole failure through the creation of BOs and DITFs is a result of stress perturbations that exist under such conditions (Kirsch, 1898; Plumb & Hickman, 1985; Zheng et al., 1989; Zoback et al., 1985). BOS are zones of compressive failure owing to the redistribution of in situ stresses around a borehole, as defined by the Kirsch equations (Jaeger et al., 1979; Kirsch, 1898), and form through wellbore spalling along the minimum horizontal stress azimuth whereas DITFs represent zones of tensile failure at the borehole wall in the maximum horizontal stress azimuth (Figure 6).

Both BOs and DITFs can be readily identified on electrical resistivity image logs. On these logs BOs are represented by two diffuse, conductive zones approximately 180° apart running parallel to the borehole axis (Figure 6).
These zones are caused by poor contact of the resistivity imaging tool with the borehole wall over the zones of BO spalling. DITFs are identifiable as vertical fractures 180° opposed running parallel or subparallel to the borehole axis (Figure 6). As DITFs represent distinct fractures, they are generally much sharper and narrower than BOs.

Failure derived $\sigma_H$ orientations are ranked according to the quality ranking system of the World Stress Map (WSM; Heidbach et al., 2010). Originally established by Zoback (1992), the WSM classification scheme defines A–C quality indicators as providing reliable $\sigma_H$ orientations for plate-scale stress analysis, whereas D–E quality indicators are thought to be unreliable. Tingay et al. (2005) demonstrate that D quality indicators can provide reliable estimates of $\sigma_H$ orientations for basin-scale investigations. Indicator quality is assigned to each well based on the number of interpreted stress indicators, total indicator length, and the standard deviation of the derived stress orientation (Heidbach et al., 2018). Because of these factors, this study only uses A–D quality indicators for the interpretation of $\sigma_H$ orientations.

A total of 1140 BOs and 183 DITFs were identified in the 15 image logs interpreted in this study, including refined interpretations of the five wells published by Bailey and Henson (2019) and resulting in a mean $\sigma_H$ orientation of 054°N (SD = 14.7°) for the Canning Basin (Figure 7) (Tables 1 and 2). The well Victory 1 was unable to be interpreted owing to the lack of orientation data (Lang, 2015). Prior Canning Basin stress studies have been collated into the Australian Stress Map database of Rajabi et al. (2017) and present a mean $\sigma_H$ orientation of 053°N for the Canning Basin Stress Province (Figure 7). Reliability of a derived regional $\sigma_H$ orientation can be statistically tested by applying the Rayleigh test, which tests for a null hypothesis that $\sigma_H$ orientations are random (Mardia, 1975). A mean resultant vector ($R$) for $\sigma_H$ orientations is calculated, and compared against a critical cutoff value for a specific confidence level. If $R$ exceeds the cutoff value, the null hypothesis is rejected (Coblentz & Richardson, 1995; Mardia, 1975; Reynolds et al., 2002). For these Canning Basin data, an $R$ of 0.967 is calculated for 24 derived $\sigma_H$ orientations, and compared with a 99% confidence cutoff of 0.432. As $R$ is greater than the cutoff, the null hypothesis is rejected, and the mean $\sigma_H$ orientation of 054°N can be applied to the larger area with confidence, as there is only a 1% chance that it is a random orientation.

**Stress rotation within Ungani North 1**

The well Ungani North 1 hosts numerous BOs and DITFs that broadly suggest a northeast–southwest $\sigma_H$ orientation. However, a noticeable change in $\sigma_H$ orientation is observed throughout the section 3000–3275 m (Figure 8), where indicators gradually rotate from the broader orientation identified in the well (~050°N) towards a more east–west $\sigma_H$ orientation of 074°N (Table 3). Below 3275 m depth, the
Table 2. Interpreted maximum horizontal stress orientations from wells hosting image logs interpreted within this study, including the criteria necessary for assigning a quality rank as per the World Stress Map criteria (Heidbach et al., 2010).

| Well            | Borehole breakouts | Drilling-induced tensile fractures |
|-----------------|--------------------|-----------------------------------|
|                 | Orientation (°)    | No. | Length (m) | SD | Quality | Orientation (°) | No. | Length (m) | SD | Quality |
| Asgard 1        | 60.2               | 253  | 896.6      | 9.1 | A       | 59.1           | 53  | 148.6      | 3.9 | A       |
| Nicolay 1       | 58.2               | 33   | 78.4       | 24.1 | C       | –              | –   | –          | –   | –       |
| Pictor East 1   | 43                 | 11   | 14.8       | 11.9 | D       | 39.1           | 40  | 104.48     | 9.6 | A       |
| Praslin 1       | 70.7               | 85   | 56.4       | 10.8 | B       | –              | –   | –          | –   | –       |
| Senagi 1        | 49.6               | 5    | 5.9        | 18.9 | D       | –              | –   | –          | –   | –       |
| Theia 1         | 60.3               | 49   | 40         | 16.7 | B       | 66.5           | 6   | 6.1        | 2.9 | D       |
| Ungani 2        | 31.3               | 17   | 69.7       | 7.4  | B       | 44.4           | 2   | 2.9        | 1.8 | D       |
| Ungani 3        | 43.2               | 74   | 184.1      | 7.3  | A       | 39.6           | 7   | 46.7       | 7.9 | B       |
| Ungani Far West 1 | 27.1             | 2    | 0.8        | 0.6  | D       | 44.1           | 1   | 0.4        | 0   | D       |
| Ungani North 1  | 49.9               | 133  | 456.9      | 11.9 | A       | 54.1           | 11  | 15         | 17.7| D       |
| Valentine 1     | 57.6               | 77   | 312.9      | 8.3  | A       | –              | –   | –          | –   | –       |
| Valhalla 2      | 42.5               | 54   | 219.2      | 11.5 | A       | 46.7           | 52  | 328.2      | 12.4| B       |
| Victory 1a      | –                  | –    | –          | –    | –       | –              | –   | –          | –   | –       |
| Yulleroo 3      | 63.5               | 173  | 887.1      | 9.4  | A       | 51.6           | 6   | 30.1       | 7.7 | C       |
| Yulleroo 4      | 64.2               | 174  | 696.3      | 9.8  | A       | 65.4           | 5   | 13.1       | 2.5 | D       |

*Victory 1 hosts an ultrasonic image log of high quality; however, the orientation module was not run with the tool, and so no stress data can be obtained for this purpose.

Figure 8. Rose diagrams demonstrating interpreted orientations of stress induced wellbore failure within the well Ungani North 1/Ungani North 1 Deepening. Data from the majority of the study interval demonstrate an approximately northeast–southwest maximum horizontal stress orientation as illustrated by the black arrows, whereas data from the interval 3000–3275 m demonstrate a rotation to an approximately east-northeast–west-southwest maximum horizontal stress azimuth. Borehole breakout orientations (red) are non-corrected.
orientation of identified indicators returns to the northeast–southwest azimuth observed through the upper portion of the well down to 3000 m depth (Figure 8). We attribute this to localised stress variation within the well, likely caused by a significant fracture and fault zone as imaged at ~3275 m depth (Figure 8). The BOs and DITFs within this interval of localised stress rotation are omitted from the calculation of regional present-day \( \sigma_H \) orientation (Tables 2 and 3).

**Comparison with earthquake data**

The approximately northeast–southwest striking mean \( \sigma_H \) orientation of 054°N derived in this study from wellbore-failure features is in broad agreement with similar past studies (e.g. Bailey & Henson, 2018; Hillis & Reynolds, 2000, 2003; Rajabi et al., 2017) as well as measurements derived from earthquake focal mechanism data. Where observations are made from a sufficiently high number of stations and with a broad azimuthal distribution, focal mechanisms determining \( \sigma_H \) orientation and failure type can be inferred from earthquake events (Rajabi et al., 2017). While numerous earthquakes occur within the Australian continental crust, the relatively low level of seismicity in Australia, combined with the regional nature of the seismic monitoring network, means that, generally, focal mechanism solutions are only resolved for the largest earthquakes (Hillis & Reynolds, 2003). An ML 6.7 earthquake was recorded in the eastern Canning Basin in March 1970. This event was assumed to have occurred at a depth of 8 km (±3 km) with an approximately northeast–southwest to north–south pressure axis in an area with no evidence of previous seismicity (Denham et al., 1974; Fredrich et al., 1988). The solution proposed by Fredrich et al. (1988) describes an almost pure thrust faulting event, as opposed to the solutions of Fitch et al. (1973) and Denham et al. (1974) who suggest an additional strike-slip component. However, although this event is interpreted to have occurred in the upper crust, the thickness of the Kidson Sub-basin is thought to be ~6.4 km (Carr et al., 2020; Department of Mines & Petroleum, 2017; Southby et al., 2020). Hence, it is likely that this earthquake occurred within the underlying basement and not the sedimentary succession, which is the subject of this study (Fredrich et al., 1988). The first motion solution presented in Denham et al. (1974) suggests a northeast–southwest pressure axis, and later work by Fredrich et al. (1988) produced a solution striking roughly north. These orientations are in broad agreement with the northeast–southwest-striking mean \( \sigma_H \) orientation interpreted in this study.

**Mechanical rock properties**

Mechanical properties control the amount of stress that can be supported by a given lithology, based on how much that lithology will deform and redistribute that stress (Figure 9). Fundamentally, low Poisson’s Ratio rocks with a high Young’s Modulus support anisotropic horizontal stresses (i.e. lower magnitudes in the minimum horizontal stress direction and elevated magnitudes in the maximum horizontal stress direction) (Figure 9), as they conduct those stresses without deforming. Conversely, rocks with a high Poisson’s Ratio and low Young’s Modulus are incapable of supporting those anisotropies and so tend towards more isotropic stresses (i.e. higher magnitudes in the minimum horizontal stress direction and lower magnitudes in the maximum horizontal stress direction) (Figure 9), as they deform and redistribute stresses as they are applied (Plumb et al., 2000). Typically, it is grain-supported facies such as sandstones or carbonates that exhibit anisotropic horizontal stresses, and clay-supported facies such as mudstones and shale that approach isotropic stress conditions (Plumb et al., 2000; Zoback, 2007).

A detailed understanding of mechanical rock properties is essential for building 1D MEMs, as they are a numerical representation of rock properties and stress states for a specific stratigraphic section (Figure 9) (Plumb et al., 2000). When fully developed, 1D MEMs provide a full description of pore pressure, stress and mechanical properties. However, owing to data constraints, model complexity generally varies between wells, fields and basins (Plumb et al., 2000). In practice, construction of a 1D MEM requires measurements of five properties: bulk rock density, static Young’s Modulus, static Poisson’s Ratio, uniaxial compressive stress and tensile strength (Brooke-Barnett et al., 2015; Plumb et al., 2000). Density is logged in almost all wells and sonic logs (both compressional and shear are commonly acquired), allowing for the calculation of dynamic velocity-based moduli from empirical relationships (e.g. Chang et al., 2006). However, conversion of these dynamic properties to static properties requires discrete measurements from laboratory tests that are undertaken far less frequently. In this study, dynamic to static transformations of Young’s Modulus and Poisson’s Ratio are derived from previously published mechanical rock testing data (Delle

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**Table 3.** Interpreted stress rotation within interval 3000–3275 m in Ungani North 1.

| Interval          | Drilling-induced tensile fractures | Borehole breakouts |
|-------------------|-----------------------------------|-------------------|
|                   | Orientation (°) | No. | Length (m) | SD | Orientation (°) | No. | Length (m) | SD |
| 2500–3700 (excluding 3000–3275) m depth | 49.9 | 133 | 456.9 | 11.9 | 54.1 | 11 | 15 | 17.7 |
| 3000–3275 m      | 73.7 | 85 | 171.97 | 12.5 | 75.1 | 10 | 85 | 12.1 |

This data are visualised in Figure 8 as rose diagrams. The data demonstrate an approximately 20° rotation of maximum horizontal stress azimuth into an interpreted fracture zone, before a return to the regional northeast–southwest norm below that feature.
Horizontal stress magnitudes from the mechanical earth model

Changes in magnitude of the three principal stresses with depth are defined by 1 D MEMs (Figure 9) constructed from wireline log data using Equation 1 to calculate $\sigma_v$ and poroelastic stress equations (Thiercelin & Plumb, 1994) that take tectonic strain into consideration to calculate $\sigma_H$ and $\sigma_h$ (e.g. Brooke-Barnett et al., 2015):

$$\sigma_H = \frac{V_{\text{stat}}}{1 - V_{\text{stat}}} (\sigma_v - \alpha P_p) + \frac{E_{\text{stat}}}{1 - V_{\text{stat}}} (\varepsilon_{\max} + V_{\text{stat}}\varepsilon_{\min})$$

$$\sigma_h = \frac{V_{\text{stat}}}{1 - V_{\text{stat}}} (\sigma_v - \alpha P_p) + \frac{E_{\text{stat}}}{1 - V_{\text{stat}}} (\varepsilon_{\min} + V_{\text{stat}}\varepsilon_{\max})$$

where $V_{\text{stat}}$ is the statically corrected Poisson’s Ratio (unitless), $\alpha$ is Biot’s Poroelastic Coefficient (unitless, assumed $\alpha = 1$), $P_p$ is the pore pressure (Pa), $E_{\text{stat}}$ is the statically corrected Young’s Modulus (Pa), $\varepsilon_{\min}$ is the strain in the minimum stress direction (unitless), and $\varepsilon_{\max}$ is the strain in the maximum stress direction (unitless). The dynamic Poisson’s Ratio and Young’s Modulus were derived from logged compressional and shear sonic data in each well and calibrated to static laboratory measurements. Empirical relationships were used to derive compressive rock strength values (Chang et al., 2006). Numerous reliable hydraulic fracture tests at multiple depths are typically required to appropriately calibrate 1 D MEMs, and although many wells contain leak off tests (LOTs), extended leak-off tests (XLOTs/ELOTs) or formation integrity tests (FITs), these are not sufficient to fully constrain horizontal stress magnitudes in the 1 D MEMs. Fifteen 1 D MEMs were constructed in this study (Figure 10); however, accurate calibration for these is challenging, owing to the majority of available LOTs having been conducted at depths of $<1$ km (Figure 10, Table 4). Although FITs are more commonly available than LOTs, and are generally undertaken more frequently during drilling, they are only suitable as a guide to the lower bound of $\sigma_h$ magnitude, as the well is not taken to failure (White et al., 2002). Calibration was also achieved through modelling of observed BO in image logs; where BOs have been imaged in sufficient quality to accurately assess the opening angle, stress magnitudes around the borehole can be constrained (Moos & Zoback, 1990). Numerous BOs were modelled as part of this study in order to obtain constraints on $\sigma_H$ and $\sigma_h$, and these were used to calibrate the constructed 1 D MEMs (Figure 10). Each model is calibrated on suitable data points (both LOTs and
modelled BOs) using an iterative process of adjusting tectonic strain values in Equations 2 and 3 from initial generic values of 0.0009 for strain in the maximum stress direction and 0.0003 for strain in the minimum stress direction (after Brooke-Barnett et al., 2015). The final 1D MEM stress profiles produced in this study are presented in Figure 10.

Figure 10. One-dimensional mechanical earth models (1D MEMs) constructed to interpret present-day stress in the Canning Basin in this study. Well locations are on Figure 1. Leak-off test data used for calibration are presented in Table 4.
Calibrated stress profiles in the Canning Basin demonstrate a dominantly strike-slip faulting stress regime, broadly agreeing with the stress regime defined by Bailey and Henson (2018) and Rajabi et al. (2017). Lithologically driven transitional zones are prevalent throughout the section (Figure 10), and broadly, 1D MEMs demonstrate a gradual shift towards a normal faulting stress regime at depths greater than ~3.0 km (Figure 10). As the sonic logs...
required to construct 1D MEMs are generally only acquired over intervals of interest, shallow areas of the basin are not well covered in these data. However, models constructed for the wells Asgard 1, Commodore 1, Fruitcake 1, Robert 1, Ungani North 1 and Yulleroo 4 feature data from shallower than 1 km, and the models indicate that the near-surface is likely to host a reverse-faulting stress regime (Figure 10). This is in line with the findings of the Australian Stress Map update (Rajabi et al., 2017), which notes that neotectonics and the Australian Stress Map database support a prevailing reverse-faulting stress regime in the upper 1 km of the Australian continent, and that this regime changes with depth.

**Implications for the development of unconventional resources**

Significant variation of the stress regime with depth in the Canning Basin is likely to act as an impediment to fracture propagation, as fracture growth within and between formations is likely to be controlled by stress contrasts between mechanically distinct units. For example, Figure 11 shows the 1D MEM for the Broome Platform exploration well Theia 1. The Goldwyer III shale target is interpreted to host a normal faulting stress regime ($\sigma_h < \sigma_m < \sigma_v$), as a result of reduced horizontal stresses, due primarily to a low Young’s Modulus. Significant increases in horizontal stress magnitudes in the overlying Goldwyer II Member and the underlying Willara Formation, primarily owing to the increased Young’s Modulus of these lithologies relative to the Goldwyer III shales, mean that the Goldwyer III shale is bracketed by mechanical units that host distinctly different stress regimes (Figure 11). The Goldwyer II Member is interpreted to host a strike-slip faulting stress regime ($\sigma_h < \sigma_v < \sigma_m$) (Figure 11), and, while fractures propagate vertically under both strike-slip and normal faulting regimes, the significant increase in $\sigma_h$ magnitude will likely exert a natural control over fracture propagation. The underlying Willara Formation is also interpreted to host a strike-slip faulting stress regime with possible transitions to a reverse-faulting regime (Figure 11). Hence, any vertical fractures propagating within these formations are likely to be contained not only by the increase in horizontal stress magnitudes, but also by a change in preferred fracture propagation direction associated with possible change to a reverse-faulting stress regime within the Willara Formation (Anderson, 1951; Baumgartner & Zoback, 1989; Hossain et al., 2000; Hubbert & Willis, 1957; Sibson, 1990; Zoback, 2007). A similar mechanical separation is evident in the Goldwyer Formation within the neighbouring well Pictor East 1, on the Mowla Terrace (Figure 11), implying that contrasting mechanical units likely form regionally extensive natural fracture barriers.

Outside the Goldwyer Formation, there are numerous inter- and intra-formational mechanical barriers that would likely serve as impediments to fracture propagation (Figure 11). These mechanical barriers are evident throughout the basin in each of the wells modelled; however, they are particularly well illustrated in the Nullara to top Laurel section within the Fitzroy Trough well Ungani North 1/Ungani North 1 Deepening (Figure 12). Although all limestone-dominated, three lithologically distinct units are identified within the Nullara Formation; a lower (3660–3700 m), middle (3263–3660 m) and upper (3124–3263 m) interval (Buru Energy, 2014). The lower Nullara Formation is described as interbedded limestone and claystone, the middle Nullara Formation as interbedded limestone, claystone and siltstone, and the upper Nullara Formation as massive limestone (Figure 12). These varying lithologies result in changes in stress magnitude and regime, both between
the units and within them, as highlighted in Figure 12. Similar stress changes are observed between the Nullara Formation and overlying May River Shale, Ungani Dolomite, and the Laurel Formation (Figure 12). The Laurel Formation is similar to the Nullara Formation, in that it hosts internal lithological variation significant enough to form intra-formational stress boundaries (Figure 12). Both intra- and inter-formational stress boundaries are likely to act as fracture containment features and are present not only in the well Ungani North 1/Ungani North 1 Deepening, but throughout the wells interpreted within this study. These are likely to exist throughout the Canning Basin and provide natural barriers to fracture propagation throughout the subsurface.

Although in many instances desirable, in order to limit the propagation of induced fractures beyond a target zone, stress boundaries can also represent an impediment and complication to hydrocarbon recovery. Economic extraction of hydrocarbons from shale, tight sandstone or other low permeability reservoirs necessitates linking the wellbore to as large a volume of the reservoir as possible. This is typically achieved through a combination of horizontal drilling and hydraulic stimulation of the reservoir. Hydraulic stimulation creates permeability pathways, in the form of induced fractures, enabling fluid to migrate from the reservoir to the well. The larger these fractures, the more significant reservoir volume that is connected to the well, and the greater the potential for recovery of hydrocarbons (Bell, 1990; Bell & Babcock, 1986). The current focus of unconventional exploration in the Canning Basin is the Goldwyer III shale target (discussed above), which is bracketed above and below by stress boundaries that are likely to contain fracture propagation. Of additional benefit to potential development of this shale is that stress variations within the Goldwyer III shale itself appear to be minimal. In the well Pictor East 1, the stress regime is interpreted as a normal to strike-slip faulting stress regime based on small changes in $\sigma_{11}$ magnitude (Figure 11). As intersected in the well Theia 1, the Goldwyer III shale is characterised by a normal faulting stress regime with minimal interpreted variation to either horizontal stress magnitude (Figure 11). It is likely that induced fractures within the Goldwyer III shale will be able to propagate vertically and access a significant volume of the reservoir while being contained by surrounding mechanical units. Fracture tortuosity is likely where lithological variations result in a change in preferred

Figure 11. Mechanical earth models for the wells Pictor East 1 and Theia 1, showing both calculated Poisson’s Ratio and Young’s Modulus, as well as interpreted stress regime (as per legend Figure 10). Of particular interest is the Goldwyer Formation, which is intersected in both wells. See Figure 1 for well locations.
fracture orientation, such as in the Goldwyer III shale interval within the well Pictor East 1 (Figure 11).

While demonstrated to be poor in organic content and not a viable resource at the location of the well Theia 1, the Bongabinni Formation is another possible shale play in the Canning Basin. The 1D MEMs constructed in this study suggest that, where intersected in the well Theia 1, an interpreted strike-slip faulting stress regime means that vertical fractures are likely to propagate effectively through the rock volume owing to there being minimal variation in horizontal stress magnitudes. This would allow access to significant volume of the reservoir owing to similarities in mechanical properties with the overlying Carribuddy Group, but it appears unlikely that a containing stress boundary exists to limit fracture propagation to just the targeted sediments at the well Theia 1.

Although not presently of active interest to the hydrocarbon industry, the May River Shale described in the well Ungani North 1/Ungani North 1 Deepening is interpreted as interbedded siltstone and claystone with minor interbedded sandstone and shale. Trace hydrocarbons were identified (Buru Energy, 2014), and the 1D MEM created in this study suggests that stress properties are favourable for an unconventional play. The overlying Ungani Dolomite...
and the underlying Nullara Formation create very effective stress boundaries (Figure 12). Within the May River Shale, there is minimal variation in horizontal stress magnitudes, although $\sigma_h$ magnitude does fluctuate enough to cause interpreted changes in dominant stress regime, flipping between strike-slip faulting at the top of the formation and into a normal faulting stress regime at the bottom of the formation (Figure 12). As in the Goldwyer III shale, induced fractures will likely propagate vertically to provide access to the reservoir, although fracture tortuosity may be an issue.

Successful development of North American shale resources is in large part dependent on the drilling of horizontal shale wells in basins with a stress regime able to sustain significant transverse vertical fractures at multiple points along the well. Despite plate boundary compression, roughly half of the continental United States is presently subject to an extensional stress regime. This is primarily the result of increased gravitational potential energy; Levandowski et al. (2018) suggested the illustrative comparison with a blob of honey spreading radially on a flat surface. Major hydrocarbon producing shales in North America such as the Devonian to Carboniferous Barnett, Bakken, Woodford and Marcellus shales (Abousleiman et al., 2007; Arthur et al., 2009; Fisher et al., 2002; Smith & Bustin, 2000) are in relaxed basins where the magnitude of $\sigma_v$ exceeds that of one or both horizontal stresses (Cook et al., 2013). That is to say, they are subject to normal or strike-slip faulting stress regimes (Heidbach et al., 2018; Levandowski et al., 2018; Zoback & Zoback, 1989) that are compatible with multi-stage transverse vertical fracturing from deep horizontal wells (Cook et al., 2013). Explorers have attempted to apply these methods to Australian shales, with little economic success, although many have demonstrated the successful initiation and propagation of vertical fractures within the target interval (Close et al., 2016; Cook et al., 2013; Johnson Jr & Titus, 2014), and early signs from the Beetaloo Sub-basin are encouraging (Altmann et al., 2018; D. Close et al., 2017; Close et al., 2016; D. I. Close et al., 2017; Revie, 2015; Sheridan et al., 2018). The Canning Basin has an advantage over many of these areas in that it is close to a significant market, is proximal to infrastructure and existing export facilities, and already has established (albeit small) production from conventional reservoirs (Hashimoto et al., 2018). Stress regimes interpreted in this study are likely conducive to the formation of significant transverse vertical fractures within potential unconventional reservoirs, particularly the Goldwyer III shale, as is seen in North American shale plays. These factors are likely to make the Canning Basin an attractive option for future unconventional shale development.

Conclusions

Wireline data interpretation reveal a variable present-day state of stress in the Canning Basin of Western Australia. An approximately northeast–southwest regional present-day maximum horizontal stress orientation is interpreted from observed wellbore failure in image logs, in broad agreement with both the Australian Stress Map and previously published earthquake focal mechanism data. One-dimensional mechanical earth models constructed for intervals from 15 Canning Basin petroleum wells, calibrated on well tests and modelled borehole failure, highlight the relationship between lithology and stress. Broadly, a strike-slip faulting stress regime is interpreted throughout the basin; however, lithological effects result in transitional stress regimes being likely (e.g. strike-slip to reverse/normal faulting). Additionally, there is a general trend from a transitional reverse- to strike-slip faulting stress regime in the top $\sim$1 km of the basin, through a strike-slip faulting stress regime to $\sim$3.0 km depth, with transitional strike-slip to normal faulting conditions becoming prevalent at depths greater than $\sim$3.0 km. As reliable hydraulic fracture tests are relatively rare in the studied wells, the stress models are primarily calibrated using borehole failure features. Localised variation of the present-day stress regime is likely due to significant lithology-driven stress variations, the influence of structural features and large $\sigma_v$ magnitude variations across the basin. This study describes significant changes in stress within and between lithological units owing to the existence of discrete mechanical units, forming numerous inter- and intra-formational stress boundaries likely to act as natural barriers to fracture propagation, particularly within units currently targeted for their unconventional resource potential. Further development of this work requires the acquisition of new rock-testing data to construct a high-resolution understanding of rock properties and allow for more constrained model calibration; detailed rock property information for each formation intersected would allow for localised calibrations rather than relying on basin-wide relationships.

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Disclosure statement

No potential conflict of interest was reported by the author(s).
Abousleiman, Y. N., Tran, M. H., Hoang, S., Bobko, C. P., Ortega, A., & Data availability statement

The authors confirm that the data that support the findings of this study are openly available in the WAPIMS at https://wapims.dmp.wa.gov.au/WAPIMS/, where each well-specific dataset can be found by searching the well name.

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