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REASSESSING THE IN-SITU STRESS REGIMES OF AUSTRALIA'S PETROLEUM BASINS

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ABSTRACT

Previous in-situ stress studies across many of Australia's petroleum basins demonstrate normal fault and strike-slip fault stress regimes, despite the sedimentary successions demonstrating evidence for widespread Miocene-to-Recent reverse faulting.

Seismic and outcrop data demonstrate late Miocene-to-Recent reverse or reverse-oblique faulting in the Otway and Gippsland basins. In the Otway Basin, a series of approximately northeast to southwest trending anticlines related to reverse-reactivation of deep syn-rift normal faults, resulting in the deformation of Cenozoic post-rift sediments are observed. Numerous examples of late Miocene-to-Recent reverse faulting in the offshore Gippsland Basin have also been observed, with contractional reactivation of previously normal faults during these times partially responsible for the formation of anticlinal hydrocarbon traps that host the Barracouta, Seahorse and Flying Fish hydrocarbon fields, adjacent to the Rosedale Fault System.

A new method for interpreting leak-off test data demonstrates that the in-situ stress data from parts of the Otway and Gippsland basins can be reinterpreted to yield reverse fault stress regimes, consistent with the present-day tectonic setting of the basins. This reinterpretation has significant implications for petroleum exploration and development in the basins. In the Otway and Gippsland basins, wells drilled parallel to the orientation of the maximum horizontal stress (σ_H) represent the safest drilling directions for both borehole stability and fluid losses. Faults and fractures, striking northeast to southwest, previously believed to be at low risk of reactivation in a normal fault or strike-slip fault stress regime are now considered to be at high risk in the reinterpreted reverse fault stress regime.

KEYWORDS

Leak-off test, reverse fault stress regime, neotectonics, southeast Australia, Otway Basin, Gippsland Basin.

INTRODUCTION

Miocene-to-Recent deformation is widespread in and adjacent to Australia's petroleum basins. High levels of seismic activity and Miocene-to-Recent tectonic activity are present in southeast Australia, southwest WA and in the North West Shelf (Keep et al, 1998; Dickenson et al, 2002; Clark and Leonard, 2003; Sandiford, 2003; Allen et al, 2005; Quigley et al, 2006; Hillis et al, 2008; Holford et al, 2011; Fig. 1). In all cases, the orientation of palaeostresses inferred from Miocene-to-Recent structures in the basins are consistent with independent determinations of the orientation of the in-situ stress field (Hillis et al, 2008; Holford et al, 2010, 2011; Fig. 1). The in-situ stress magnitudes, however, are not consistent. In the Perth, Otway and Gippsland basins, and on the North West Shelf, in-situ stress magnitudes demonstrate strike-slip fault stress regimes and, in some cases, normal fault stress regimes (Mildren, 1997; Nelson and Hillis, 2005; Nelson et al, 2006; van Ruth et al, 2006; King et al, 2008). Knowledge of the in-situ stress field is crucial to fault reactivation, seal integrity, fracture stimulation, wellbore stability, and water flood design in petroleum basins (Heffer et al, 1995; Barton et al, 1998; Nelson et al, 2005a; Tingay et al, 2009; King et al, 2010a). Thus, this disparity between measured stress magnitudes and the neotectonic evidence may be detrimental to exploration and development in Australia's petroleum basins.

In the Earth's crust, the three principal stresses (σ_1, σ_2 and σ_3) can be resolved into a vertical stress (σ_v) and two horizontal stresses (a maximum—σ_H—and a minimum—σ_h), all at 90° to one another (Anderson, 1951). The relative magnitudes of the three stresses define the three stress regimes:

1. normal fault ($\sigma_v > \sigma_H > \sigma_h$);
2. strike-slip fault ($\sigma_H > \sigma_v > \sigma_h$); and,
3. thrust or reverse fault ($\sigma_H > \sigma_h > \sigma_v$).

The magnitudes of the in-situ stress regime in a petroleum basin are commonly determined using wireline logs and drill tests. The magnitude of σ_v is equivalent to the weight of the overburden (and the weight of seawater for offshore wells) and is calculated by the integration of density logs (Jaeger and Cook, 1971; Bell, 2003; King et al, 2010b). Of the three stress magnitudes, σ_H is the most difficult to calculate, but it can be determined by a number of calculations that are defined by the relationship of σ_H with σ_v and σ_h, circumferential stresses around a borehole, rock strength, and pore pressure (Sibson, 1974; Jaeger and Cook, 1971; Bell and Gough, 1979; Nelson and Hillis, 2005). The magnitude of σ_h is determined from hydraulic fracture tests, such as mini-fracture tests and leak-off tests (LOTs; Breckels and van Eckelen, 1982; Dickey, 1986; Bell, 1990; Nelson et al, 2006). It is the determination of σ_h from LOTs that is the focus of this paper.

Immediately after casing has been set, a LOT is undertaken in a new section of open hole (Dickey, 1986). Once drilling ceases, the mud pressure is increased at a constant rate until a tensile fracture forms in the borehole wall (Dickey, 1986; Fig. 2). The occurrence of a fracture in the borehole wall results in a drop in mud pressure in the borehole; this is leak-off (Dickey, 1986). The highest pressure recorded before the leak-off occurs is the leak-off pressure (LOP; Bell, 1996; Fig. 2). The newly formed fracture is assumed to be a tensile fracture in a vertical well; it strikes parallel to the σ_H and opens against the σ_h (Bell,

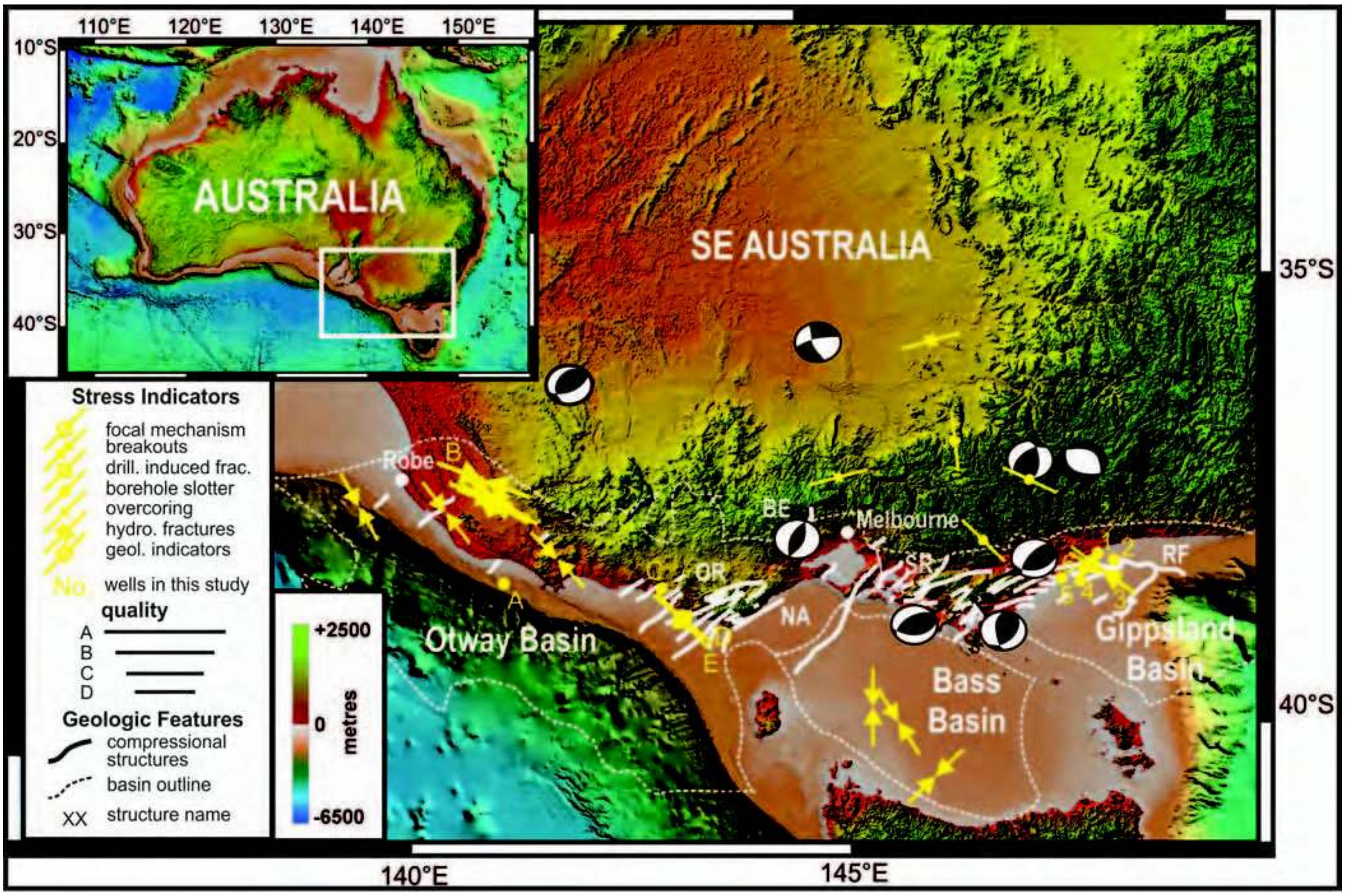

Figure 1. Location map illustrating the Otway and Gippsland basins, the mean maximum horizontal stress orientations from the Australian stress map, earthquake focal mechanisms, and Miocene-to-Recent compressional structures (Hillis and Reynolds, 2003; Sperner et al, 2003; Hillis et al, 2008; Heidbach et al, 2010; Holford et al, 2010). OR—Otway Ranges. SR—Strzelecki Ranges. LV—Latrobe Valley. NA—Nerita Anticline. RF—Rosedale Fault System. BE—location of Balliang earthquake. Inset: location map of Australia.

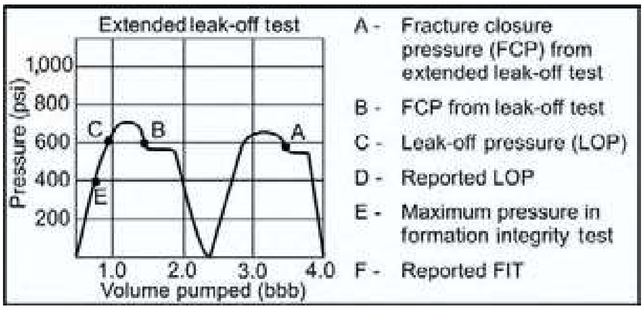

Figure 2. A time (volume pumped) versus pressure plot during a two-cycle extended leak-off test. Labelled points represent leak-off pressure (LOP) values used to estimate the σ_h.Labels indicate quality ranking for LOP estimates, with A being the highest quality and F being the lowest. Points D and F are not annotated as these are reported (usually in well completion reports) values for points C and E, respectively.

1996). Thus, the value of the LOP is used as the lower bound to the σ_h (Breckels and van Eckelen, 1982; Bell, 1990). Recent studies have, however, highlighted possible uncertainties related to interpreting the magnitude of the σ_h from LOTs (Kunze and Steiger, 1991; Gjønnes et al, 1998; Raaen et al, 2006; Couzens-Schultz and Chan, 2010). In particular, Couzens-Schultz and Chan (2010) focus on the underestimation of the magnitude of the σ_h from LOTs undertaken in thrust fault stress regimes. This problem often occurs when in-situ stress magnitude studies are used to infer a strike-slip fault stress regime rather than a thrust fault stress regime. They demonstrate that the leak-off during these LOTs is the result of the reactivation of a shear fracture, not the formation of a new tensile fracture (Couzens-Schultz and Chan, 2010). Reactivation of a shear fracture requires different interpretations to estimate the value of the σ_h (Couzens-Schultz and Chan, 2010). Couzens-Schultz and Chan (2010) have demonstrated that this new interpretation of LOTs in areas of active thrust faulting results in magnitudes that are consistent with the neotectonics observed.

In this paper, 14 LOTs from the Otway and Gippsland basins are re-interpreted using the method proposed by Couzens-Schultz and Chan (2010). This paper demonstrates that the magnitude of σ_h has been historically underestimated due to the traditional interpretation of LOTs. It is shown that thrust fault stress regimes occur at present-day in parts of these basins, which is consistent with the neotectonic evidence, seismicity, and the present-day stress orientations.

GEOLOGICAL SETTING

The geological setting for Australia's petroleum basins is wide and varied. In this paper, the focus is on the Otway and Gippsland basins on the southern passive margin of Australia. The Otway and Gippsland basins are two of several east-to-west to northwest-to-southeast trending rift basins that lie along Australia's southern margin (Fig. 1). The Otway Basin extends ~300 km northwest to southeast from Melbourne (Victoria) to Robe (SA), and is located both onshore and offshore. The Gippsland Basin is located to the east, extending ~400 km east to west from Melbourne to Cape Howe (Victoria). The basins initiated during the Late-Jurassic in response to rifting of Australia and Antarctica. Rift and sag phases continued into the

Early Cretaceous. Cretaceous to Recent phases of compression have resulted in inversion and wrenching of the pre-existing rift structures (Holford et al, 2010).

The sedimentary successions of several of the interior basins and passive margins of the Australian continent contain evidence for post-mid Eocene reverse faulting (Hillis et al, 2008), with particularly strong evidence for late Miocene-Quaternary reverse or reverse-oblique faulting in the Otway and Gippsland basins (Dickinson et al, 2001, 2002; Sandiford et al, 2004; Holford et al, 2010). In southeast Australia, the strike orientations of faults and fault-related anticlines with evidence for late Miocene-Quaternary displacement and growth are frequently orthogonal to present-day maximum horizontal stress orientations determined from both exploration wells (i.e. borehole breakouts and drilling induced tensile fractures), and from earthquake focal mechanisms (Hillis et al, 2008; Fig. 1).

The Otway Basin contains a series of approximately northeast to southwest trending anticlines related to reverse-reactivation of deep syn-rift normal faults, resulting in deformation of Cenozoic post-rift sediments (Tuitt et al, 2011). These folds grew throughout post-mid Eocene times (Tuitt et al, 2011), with the most recent deformation occurring during the late Miocene-early Pliocene in the Torquay Sub-basin (Dickinson et al, 2001, 2002; Holford et al, 2010, 2011). Seismic, stratigraphic and thermochronological evidence shows the approximately northeast to southwest striking Nerita Anticline in the Torquay Sub-basin formed between ~10–5 Ma, resulting in folding of early-mid-Miocene sediments and the erosion of up to ~1 km of late Miocene section (Holford et al, 2010). Seismic data show this anticline is underlain by approximately northeast to southwest trending normal faults that formed during late Cretaceous-early Palaeogene extension, but were contractionally reactivated during the Neogene (Holford et al, 2011). Elsewhere in the Torquay Sub-basin, shallow seismic records collected offshore and adjacent to the Otway Ranges show folding in Pliocene sediments (Dickinson et al, 2002).

The onshore and offshore successions of the Gippsland Basin also provide evidence for Miocene-onwards compression. Dickinson et al (2001) document numerous instances of late Miocene-Pliocene reverse faulting in the offshore Gippsland Basin, with contractional reactivation of previously normal faults during these times partially responsible for the formation of anticlinal hydrocarbon traps that host the Barracouta, Seahorse and Flying Fish hydrocarbon fields. Fault-related folding in these fields have resulted in the deformation of Pliocene sediments, while shallow seismic lines acquired across the Tarwhine field (adjacent to the Rosedale Fault System) reveal folding of Quaternary sediments resulting in the formation of seafloor anticlines (Dickinson et al, 2001). Most of the offshore anticlines that formed in response to late Miocene-Pliocene reverse faulting trend approximately northeast to southwest or approximately east-northeast to west-southwest (Fig. 1). Miocene-Quaternary compression has also resulted in onshore deformation in the Gippsland Basin. In addition to the Strzelecki Ranges, which like the Otway Ranges in the Otway Basin are thought to have been uplifted since the late Miocene (Dickinson et al, 2001), notable approximately northeast to southwest striking structures in the Latrobe Valley include the Yallourn Monocline and the Baragwanath Anticline (adjacent to the Rosedale Fault System). A major angular unconformity dated at ~7–4 Ma separates Pliocene units from folded Miocene sediments at the Yallourn Monocline (Barton, 1981; Dickinson et al, 2002). Reverse offset observed on the Yallourn Fault, as exposed in the Yallourn coal mine, constrains the timing of deformation to pre-Pliocene (i.e. latest Miocene; Dickinson et al, 2002). Younger compressional deformation is evident by the approximately northeast to southwest trending Baragwanath Anticline, which is bounded by the Rosedale Fault (Holdgate et al, 2003). This anticline is elevated along its crest from 30–60 m above the flood plain of the Latrobe River, and magnetic images show that it is crossed by several fluvial channels of early-middle Pleistocene palaeorivers (Holdgate et al, 2003). Holdgate et al (2003) attributed the uplift of this anticline to between ~60–100 m of early-mid Pleistocene (~1.5–0.25 Ma) movement on the Rosedale Fault.

PUBLISHED STRESS DATA FROM AUSTRALIA'S PETROLEUM BASINS

The Australian stress map was originally set-up to improve the limited understanding of in-situ stress fields of Australia (Hillis and Reynolds, 2003). To date, 393 stress orientations have been recorded on the Australian stress map since its inception (Heidbach et al, 2010). They have largely been determined from petroleum well data, earthquake focal mechanisms, and some mining data (Hillis and Reynolds, 2003; Heidbach et al, 2010). The first-order stress orientations across the Indo-Australian Plate are not, like other tectonic plates, parallel or sub-parallel to absolute plate motion (Richardson, 1992), but are controlled by complex plate boundaries (Reynolds et al, 2002, 2003). Maximum horizontal stress orientations across Australia are broadly east to west in WA, rotating north to south across northern Australia and parts of central Australia, and rotating to a northwest to southeast orientation in southeast Australia (Hillis and Reynolds, 2003).

Nelson et al (2006) have determined the σ_H orientations in the western (SA) and eastern (Victoria) parts of the Otway Basin to be ~125°N and ~135°N, respectively. The approximately northwest to southeast-directed σ_H orientations in the Otway Basin are consistent with the approximately northeast to southwest trends of structures formed during late Miocene-early Pliocene deformation (Hillis et al, 2008; Fig. 1). Few independent constraints on present-day stress orientations from earthquake focal mechanisms are available for the Otway Basin. Denham et al (1981), however, produced a fault-plane solution for an earthquake that measured 4.8 on the Richter scale (local magnitude) in December 1977, in Balliang, Victoria—just to the north of the basin—which revealed a reverse-faulting mechanism due to a approximately northwest to southeast compressional stress regime (Fig. 1). In-situ stress magnitudes determined from petroleum well data in the Otway Basin, however, demonstrate a strike-slip fault stress regime ($\sigma_H > \sigma_v > \sigma_h$; Jones et al, 2000; Nelson et al, 2006; Tassone et al, 2011; Fig. 4A).

The in-situ, regional σ_H orientation in the Gippsland Basin, constrained by 118 (A–C quality) breakouts in 11 wells, is ~139°N, indicating a ~15° anticlockwise rotation in the σ_H from the western Otway Basin (Nelson et al, 2006). As with the Otway Basin, the approximately northwest to southeast σ_H orientation in the Gippsland Basin is consistent with the approximately northeast to southwest strike direction of late Miocene-Quaternary compressional structures (Fig. 1). The in-situ, σ_H orientation for the Gippsland Basin determined using wellbore data is in close agreement with the results from Allen et al (2005), who calculated a composite fault-plane solution using four earthquakes that occurred between 1996–2000 to the immediate north of the Gippsland Basin. These solutions indicated a reverse fault mechanism with the σ_H oriented at 145°N (Fig. 1). In-situ stress magnitudes have also been determined from petroleum well data in the Gippsland Basin and give a borderline reverse fault to strike-slip fault stress regime (Nelson et al, 2005b; Nelson and Hillis, 2005; Nelson et al, 2006; van Ruth et al, 2006). Although the magnitudes strictly demonstrated a strike-slip fault regime, researchers state a borderline reverse fault to strike-slip fault stress regime to account for the recent compressional structures and seisimic events. This is symptomatic of stress magnitudes interpretations across Australia, where well data often demonstrates a strike-slip stress regime, but neoteconics and seismicity indicate a reverse fault stress regime (Nelson et al, 2005b; Nelson and Hillis, 2005; Nelson et al, 2006; King et al, 2008).

THE MINIMUM HORIZONTAL STRESS MAGNITUDE

Traditional interpretation of leak-off tests

The magnitude of the σ_h has been estimated from leak-off pressures recorded during leak-off tests (LOTs). These tests are carried out during drilling operations. The tests involve increasing the pressure of the borehole fluid in a small section (< 3 m) of newly drilled well, immediately after the casing has been set (Dickey, 1986). During the test, the pressure is increased until a fracture has formed at the borehole wall (Dickey, 1986; Fig. 2). Fracture formation is marked by a change in slope on a pressure versus time plot and is referred to as the leak-off pressure (LOP; Fig. 2). The traditional interpretation of a LOT assumes the formation of a new tensile fracture. In most cases, the fracture forms vertically, striking in the direction of σ_H, and opens against (orthogonal to) the σ_h. Thus, LOPs provide the best estimate of σ_h (Bell, 1996), and can be summarised in Equation 1.

$$c \frac{\partial p}{} \frac{\nabla .u)}{} = \nabla . \left| \frac{k}{} .\nabla p \right| \tag{1}$$

ρ_m is the mud weight of the fluid used during the LOT, g is acceleration due to gravity, and z is depth.

Values of σ_h estimated from LOTs are qualified by the completeness of the LOT cycle (i.e. the pressure versus time (or volume pumped) graph; Fig. 2). Fracture closure pressures from extended LOTs give the most reliable estimates of σ_h, while formation integrity tests give the least reliable value for σ_h (Addis et al, 1998; White et al, 2002; King et al, 2008).

New method for interpreting leak-off tests

A new method for interpreting leak-off tests in regions of active thrust or reverse faulting demonstrates that the LOP is a result of failure on a pre-existing shear fracture and is not due to the formation of a new vertical tensile fracture (Couzens-Schultz and Chan, 2010). This approach is similar to the standard LOT interpretation, which assumes minimum stress is simply related to the opening of existing fractures (Couzens-Schultz and Chan, 2010). The fracture induced during fluid-pressure increases fails by shear, however, due to the relatively large differential far-field stresses associated with a regional reverse/thrust fault stress regime (Couzens-Schultz and Chan, 2010). Shear creates mixed mode fractures that result in open volumes in the surrounding rock, allowing fluid to bleed away (Couzens-Schultz and Chan, 2010). It has been shown that a pressure versus volume graph giving a curved shape—rather than a long, linear build-up—is more likely to be the result of shear failure (Couzens-Schultz and Chan, 2010). Thus, the regional stress regime can be calculated by inverting the LOT, assuming shear failure instead of tensile failure following Equations 2 and 3. Couzens-Schultz and Chan (2010) use the Mohr-Coulomb failure criteria to produce a set of Mohr circles associated with potential shear failure along a pre-existing fracture. Assuming σ_v is one of the three principal stresses, this set of Mohr circles define a minimum (σ_h,lim) and maximum (σ_H,lim) limit of stress (Fig. 3).

$$(\lambda + G)\frac{\nabla .u}{\partial x_i} + G\nabla^2 u_i - \alpha \frac{\partial p}{\partial x_i} = 0 \tag{2}$$

$$\left[\overrightarrow{\overrightarrow{M_5}} \quad \overrightarrow{\overrightarrow{M_3}}^{T} \right] \left[\Delta \overrightarrow{U}^{i} \right] = \left[\overline{f_2} \right. \tag{3}$$

Co is cohesion and μ is the coefficient of friction (tan□).

This new method demonstrates that the traditional assumption of a newly formed vertical tensile fracture during a LOT will typically underestimate the magnitude of the σ_h, so that it is never greater than σ_v. Thus, a reverse fault or thrust fault stress regime will not result from stress analysis. It could be argued that shear failure of a pre-existing fracture is unlikely to occur, and that a new tensile fracture will always form during a leak-off test. In the case of a reverse fault or thrust fault stress regime, however, the minimum principal stress (σ_3) is vertical. Thus, any newly forming tensile fracture will be horizontal. Hence, the LOP will be equivalent to the magnitude of σ_v, and not the σ_h.

Interpretation of leak-off tests in Australia's petroleum basins

Values of σ_h have been estimated using both methods of interpretation from five LOTs in the Otway Basin and nine LOTs in the Gippsland Basin (Table 1; Fig. 4). These LOTs were taken from published data (Nelson et al, 2006). In the Otway Basin, the traditional method of LOT interpretation yields values of σ_h that range from 12.6 MPa at 820.0 m in Lavers–1, to 43.0 MPa at 1,995.7 m in Minerva–1 (Table 1; Fig. 4; Nelson et al, 2006). In the Gippsland Basin, the use of the traditional method of interpretation generated values of σ_h that range from 5.9 MPa at 311.0 m in Basker–1, to 50.4 MPa at 2,894.0 m in Tuna–4 (Table 1; Fig. 4; Nelson et al, 2006).

The new method of LOT interpretation presented by Couzens-Schultz and Chan (2010) has been applied to these same LOTs interpreted by Nelson et al (2006). In the Otway Basin, the new values of σ_h range from 14.1 MPa at 820.0 m

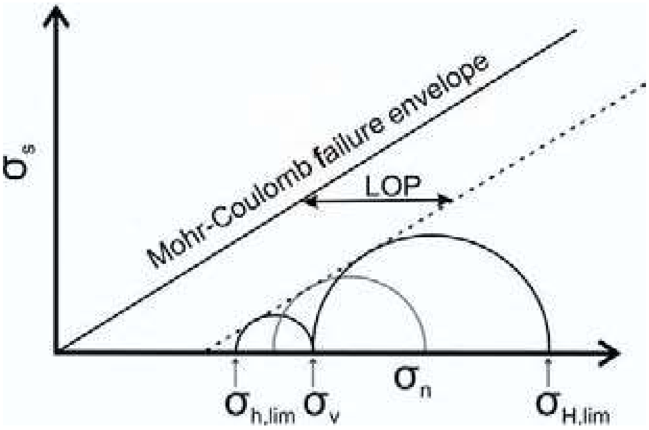

Figure 3. The stress regime can be defined using a set of Mohr circles (graph of normal stress—σ_n—versus shear stress—σ_s), and the known vertical stress (σ_v). To the far left, the Mohr circle illustrates a possible normal fault stress regime defined by the vertical stress (σ_v) and the lower limit of the minimum horizontal stress ($\sigma_{h,lim}$). To the right, the Mohr circle shows a reverse fault or thrust fault stress regime defined by the vertical stress (σ_v) and the upper limit of the maximum horizontal stress ($\sigma_{H,lim}$). The central, grey Mohr circle represents one of many possible strike-slip stress regime between the two black Mohr's circles. During the leak-off test, failure will occur by movement of the Mohr circles toward the failure envelope (by a distance equivalent to the leak-off pressure).

in Lavers–1, to 39.0 MPa at 1,995.7 m in Minerva–1 (Table 1; Fig. 4). In the Gippsland Basin, the newly derived values of σ_h range from 6.7 MPa at 311.0 m in Basker–1, to 56.0 MPa at 2,894.0 m in Tuna–4 (Table 1; Fig. 4). In each basin, the new interpretation produces equal or higher values for σ_h compared to the traditional interpretation, with differences ranging from 1.48–2.65 MPa in the Otway Basin, and 0.13–7.01 MPa in the Gippsland Basin (Table 1; Fig. 4).

The frictional limits equation (Eq. 4) constrains the allowable stress states for a given region.

$$\frac{\sigma1-Pp}{\sigma3-Pp} \leq \left(\sqrt{(\mu^2+1)}+\mu\right)^2 \qquad (4)$$

Pp is pore fluid pressure (here assumed to be 9.8 MPa/km), and μ is the coefficient of friction (here assumed to be 0.6; after Byerlee, 1978). These allowable stress states are represented by an allowable regions diagram where all possible stress states sit in the polygon defined by the outer black line and the grey diagonal line (Fig. 5). The criterion—$\sigma_H > \sigma_h$—constrains the possible stress states above the diagonal grey line. The central black lines represent $\sigma_H = \sigma_v$ and $\sigma_h = \sigma_v$, and these separate the normal fault (NF), strike-slip fault (SS), and reverse fault (RF) stress regimes. Figure 5 illustrates four examples from the Otway Basin (Minerva–1 (A) and Discovery Bay–1 (B)) and Gippsland Basin (Tuna–4 (C) and Basker–1 (D)). In each case, the area enclosed by the dashed grey line and the outer black lines defines the allowable stress states based on the traditional interpretation of LOTs; it should be noted that not one allows for a reverse fault stress regime (Fig. 5). In each case, the new interpretation of LOTs produces a lower bound for the value of the σ_h. The red line defines the allowable stress state based on these new leak-off test interpretations (after Couzens-Schultz and Chan, 2010) and in each case, all three of the stress regimes are allowable. Most importantly, a reverse fault stress regime is possible, remembering the values of σ_h are only a lower bound, and not the actual value (Fig. 5). The actual value of σ_h can be any number between this lower bound and the lower bound value for σ_H. These new LOT interpretations are consistent with the overwhelming neotectonic evidence and recent seismicity in the Otway and Gippsland basins, which was not previously the case for stress magnitudes determined using the traditional method of LOT interpretation. While this new interpretation also allows for normal fault and strike-slip fault stress regimes, it does allow for a reverse fault stress regime, which the traditional interpretations do not.

IMPLICATIONS FOR PETROLEUM EXPLORATION AND DEVELOPMENT

It has been demonstrated in previous studies that the orientations and magnitudes of present-day stresses are critical to borehole stability, water flooding, fracture stimulation, and fault reactivation (Heffer et al, 1995; Barton et al, 1998; Tingay et al, 2003; Nelson et al, 2005a; Tingay et al, 2009). Examples of borehole stability and fault reactivation in the Otway and Gippsland basins are presented using the:

- published stress magnitudes, which were calculated using the traditional method for LOT interpretations; and,
- stress magnitudes presented herein, which were calculated using the new method for LOT interpretation, (after Couzens-Schutlz and Chan, 2010).

Table 1. Estimates of the minimum horizontal stress from LOTs carried out in wells in the Otway and Gippsland basins. The table presents the magnitudes of the minimum horizontal stress using the traditional interpretation of LOTs and the new method for interpretation (after Couzens-Schultz and Chan, 2010). Numbers or letters preceding well names correspond to the location of wells in Figure 1.

Well	Latitude	Longitude	Depth (m)	Estimated minimum horizontal stress using traditional interpretation (MPa)	Estimated minimum horizontal stress using new interpretation (MPa)	Vertical stress magnitude derived from density logs (MPa)
Gippsland Basin						
(1)Baleen–1	-38.0102	148.4357	598.7	12.3	12.4	12.7
(2)Basker–1 (A)	-38.3074	148.6981	311.0	5.9	6.7	8.2
(2)Basker–1 (B)			917.0	21.2	21.4	21.5
(2)Basker–1 (C)			2,666.0	43.5	50.5	65.3
(3)Blackback–1	-38.5510	148.5617	2,526.0	42.0	49.0	63.8
(4)Halibut–1	-38.3989	148.3164	733.0	15.3	15.6	15.9
(5)Snapper–4	-38.2151	148.0039	1,365.0	28.1	28.6	29.7
(6)Tuna–4 (A)	-38.1892	148.3689	2,354.0	47.4	49.2	52.9
(6)Tuna–4 (B)			2,894.0	50.4	56.0	67.8
Otway Basin						
(A)Discovery Bay–1	-38.41	141.07	1,121.0	16.3	19.0	24.5
(B)Hungerford–1	-37.45	140.60	1,009.0	13.6	16.1	21.1
(C)Lavers–1	-38.48	142.80	820.0	12.6	14.1	17.2
(D)Minerva–1	-38.70	142.95	1,995.7	37.0	39.0	43.0
(E)Minerva–2	-38.72	142.96	1,415.7	25.1	27.0	30.9

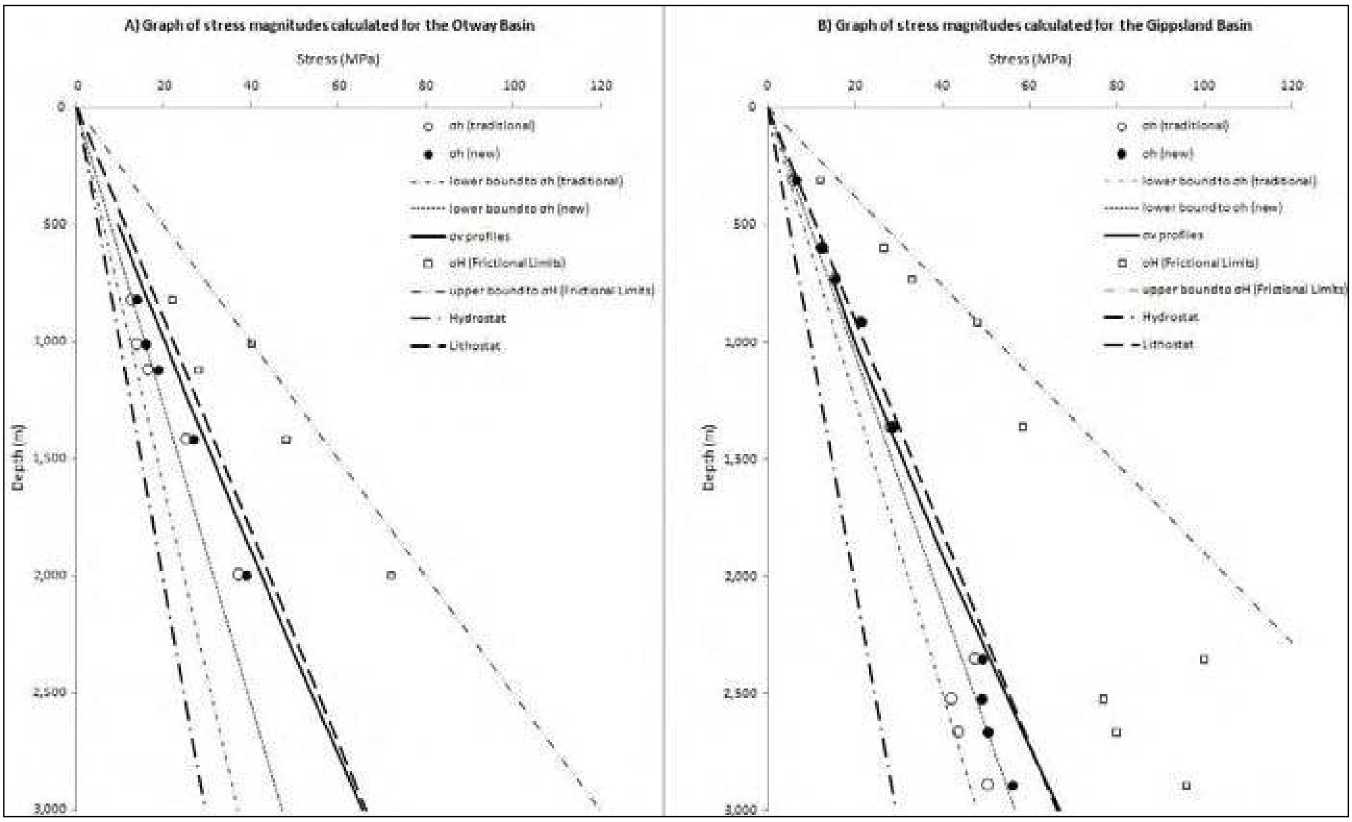

Figure 4. Graphs illustrating the stress magnitudes in the Otway (A) and Gippsland (B) basins. Each graph demonstrates Nelson et al's (2006) original values for the vertical stress (σ_v; solid black lines) calculated from density logs, the minimum horizontal stress (σ_h; open circles) derived from the traditional interpretation of leak-off tests, and the maximum horizontal stress (σ_H; open squares). Each graph also shows the values of the minimum horizontal stress magnitudes (σ_h) derived from the new method of interpretation (closed black circles).

Borehole stability

Boreholes can become unstable, in the form of borehole breakouts or drilling-induced tensile fractures, due to the anisotropy of the stress field. Thus, boreholes are most stable when drilled in a direction that subjects the well to the least amount of stress anisotropy. In a reverse fault stress regime, the greatest stress anisotropy occurs between the σ_H and σ_v. Therefore, vertical wells and horizontal wells drilled toward σ_h are the least stable because they are subject to the greatest stress anisotropy between σ_H and σ_v (Fig. 6A). The most stable drilling direction will be in the direction of σ_H, as wells drilled in this direction are subject to the least amount of stress anisotropy between σ_v and σ_h (Fig. 6A). If, however, the difference between the two horizontal stresses is small, vertical wells may be stable, but this is not the case in the Otway and Gippsland basins (Fig. 6A). In a strike-slip stress regime, the greatest stress anisotropy occurs between the σ_H and σ_h. Therefore, vertical wells will be the least stable, because they are subject to the greatest stress anisotropy (Fig. 6B). The most stable wells in a strike-slip stress regime are horizontal wells drilled toward σ_H because they are subject to the least stress anisotropy (Fig. 6B).

The results presented herein demonstrate that it is likely a reverse fault stress regime exists in the Otway and Gippsland basins, which requires new predictions for safe drilling directions. In the Otway and Gippsland basins, wells drilled parallel to the orientation of σ_H (N125°E and N139°E, respectively) represent the safest drilling directions for both borehole stability and fluid losses (Fig. 6A). This is important because it is contrary to previous predictions based on a strike-slip fault stress regime (Fig. 6B).

Fracture stimulation and fault reactivation

The formation and reactivation of faults and fractures is controlled by the in-situ stress regime. New faults and fractures strike parallel to the σ_H and open against the σ_h in a normal fault stress regime, they strike about 26° to the σ_H in a strike-slip fault stress regime, and in a reverse or thrust fault regime they strike parallel to the σ_H and open against σ_v (Anderson, 1951; Healy et al, 2006). Reactivation occurs on pre-existing faults and fractures in these orientations when the rock strength, stress magnitudes, and pore-fluid pressure satisfy the failure criterion (Fig. 3).

Figure 7 illustrates the reactivation potential plots for a reverse fault stress regime (A) and a strike-slip fault stress regime (B) at a depth of 1 km in the Otway and Gippsland basins (σ_H orientations are defined as N125°E and N139°E, respectively). Reactivation potential plots use Mohr circles (Means, 1976) to assess which orientations of faults and fractures are most likely to be critically stressed and therefore, most likely to be reactivated (red; Fig. 7). Each diagram plots the poles to fault planes (i.e. a stereonet) for all possible fault and fracture orientations. The colour refers to the proximity of a fault or fracture to the failure envelope if plotted on a Mohr circle, with red representing faults and fracture most likely to reactivate, and blue representing faults and fractures least likely to reactivate.

In the Otway and Gippsland basins, it is likely a reverse fault stress regime exists, as described above. This requires new predictions for the likelihood of fault and fracture reactivation to be undertaken. Thus, faults and fractures that strike northeast to southwest, perpendicular to the orientation of σ_H (N125°E and N139°E in the Otway and Gippsland basins, respectively), and dip shallowly (≤ 30°) to the northwest and southeast are most likely to reactivate (Fig. 7A). New thrust faults and new fractures

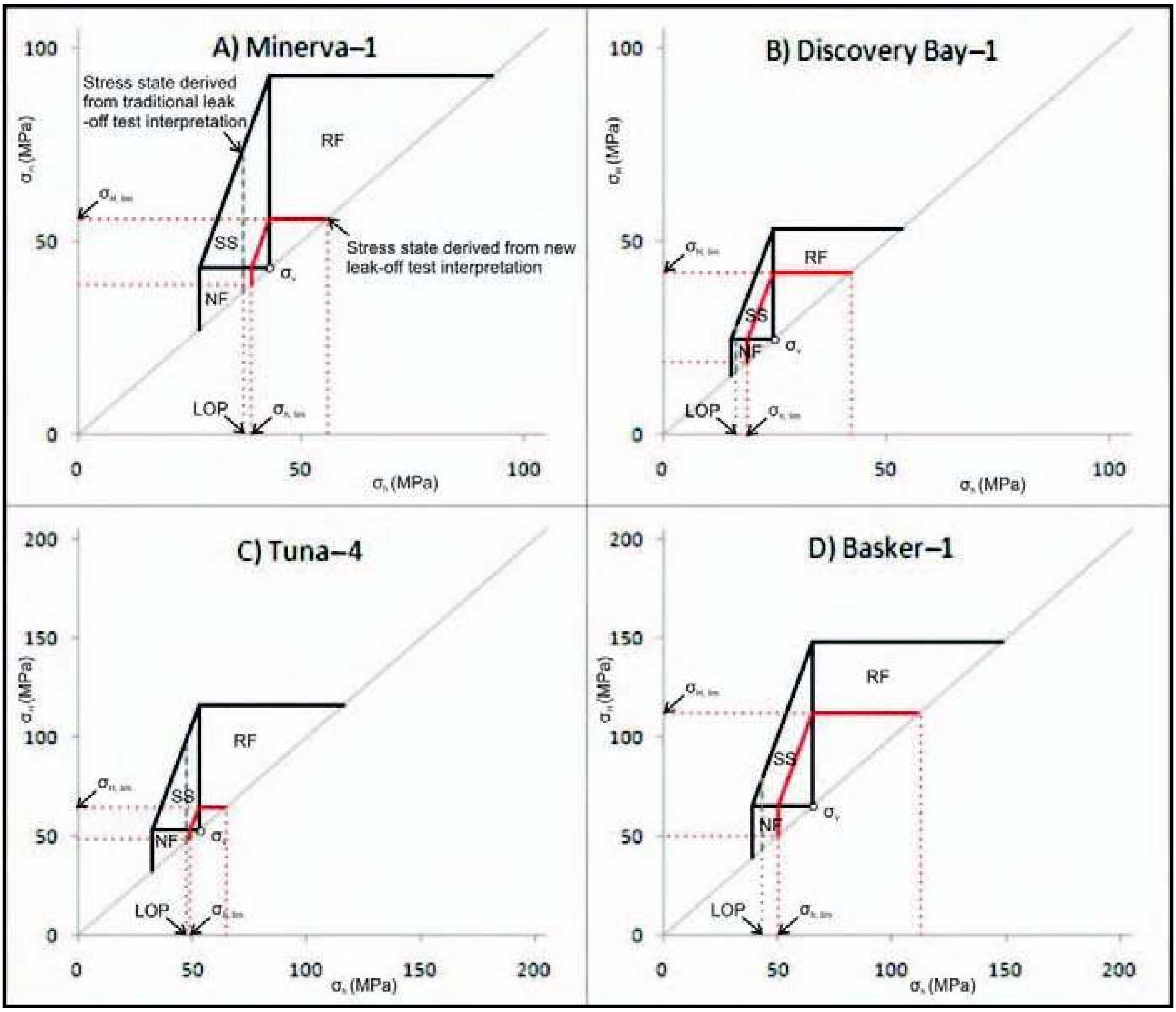

Figure 5. The frictional-limits equation constrains the allowable stress states to inside the outer black line (assuming pore-fluid pressure is 9.8 MPa/km and μ is 0.6). The criterion that the maximum horizontal stress (σ_H) is greater than the minimum horizontal stress (σ_h) constrains the possible stress states to the upper left part of the graphs, above the diagonal grey line. The central black lines represent $\sigma_H = \sigma_v$ and $\sigma_h = \sigma_v$ and separate the normal fault (NF), strike-slip fault (SS), and reverse fault (RF) stress regimes. The red line defines the allowable stress state based on the new leak-off test interpretations (after Couzens-Schultz and Chan, 2010), while the area left of the dashed grey line defines the allowable stress states based on the traditional interpretation of LOTs. In all cases, the traditional interpretation does not allow for a reverse fault stress regime. These are four examples from the Otway Basin (A and B) and the Gippsland Basin (C and D).

will also form in these orientations in the Otway and Gippsland basins. As with the new prediction for borehole stability, this is important because it is contrary to previous predictions of fault and fracture reactivations, which have been based on a strike-slip fault stress regime (Mildren et al, 2005; Fig. 7B).

CONCLUSIONS

Stress magnitudes in southeast Australia have been reassessed using a new method for interpreting LOTs (after Couzens-Schultz and Chan, 2010). The new method was applied to nine LOTs from petroleum wells across the Otway and Gippsland basins. This new method of LOT interpretation generates higher values of σ_h, the increase ranging from 0.13–7.01 MPa (Fig. 4). In some cases, the new values of σ_h are equal to or higher than the magnitude of σ_v, thus demonstrating that a reverse fault stress regime exists in parts of both the Otway and Gippsland basins (Fig. 4). These new interpretations go some way to bridging the disparity between previous stress magnitude studies and the observed, recent compressional structures and seismic events.

It is with confidence that predictions of borehole stability and fault reactivation based on a possible reverse fault stress regime can be made. This is important because previous studies have been based on a strike-slip fault stress regime. In the Otway and Gippsland basins, the most stable wells are horizontal wells drilled parallel to the orientation of σ_H (N125°E and N139°E, respectively; Fig. 6A). Faults and fractures that strike northeast to southwest, perpendicular to the σ_H, and dip shallowly are the most likely to reactivate (Fig. 7A). This includes many of the Miocene-to-Recent compressional structures observed across the basins.

ACKNOWLEDGMENTS

The authors would like to thank JRS Petroleum Research for the use and academic licensing of their software, JRS Suite. This paper forms the TRaX record number 208.

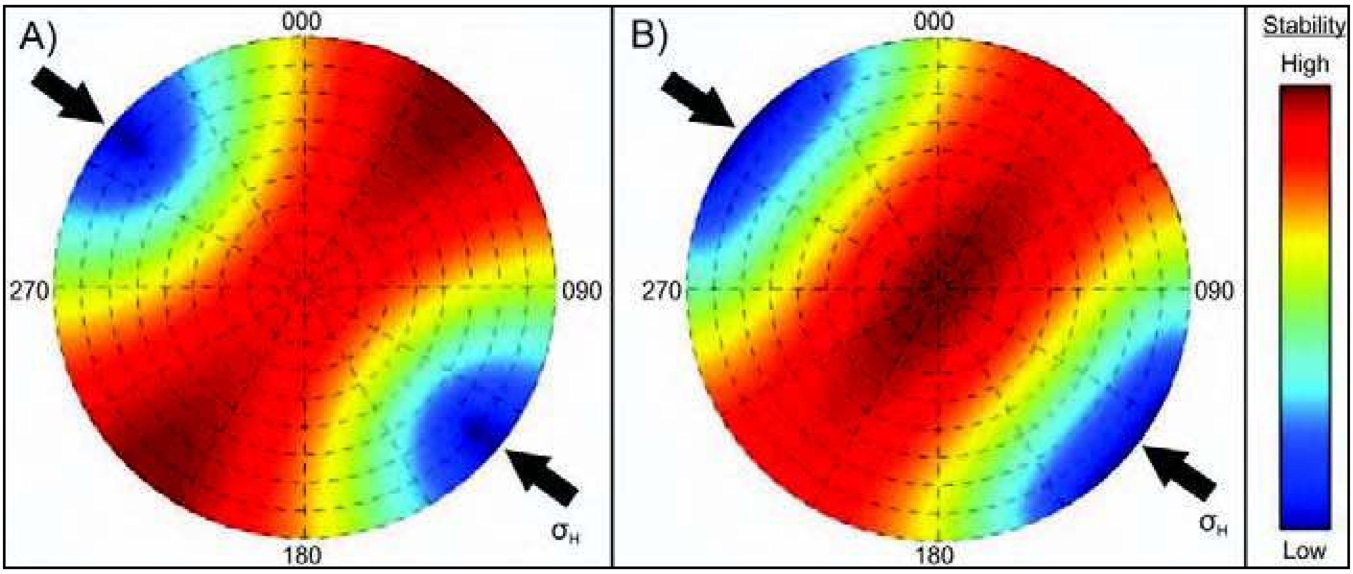

Figure 6. Borehole stability diagrams illustrating the most stable (blue) and least stable (red) wells in a reverse fault stress regime (A) and a strike-slip fault stress regime (B). The scale is relative. Vertical wells plot in the centre of the diagram and horizontal wells plot on the circumference of the diagram, with north (000) being at the top of the diagram and south at the bottom. All other wells deviated between 01° and 89° plot inside the diagram. Stress magnitudes are as follows; maximum principal stress is 40 MPa, intermediate principal stress is 20 MPa, and the minimum principal stress is 15 MPa.

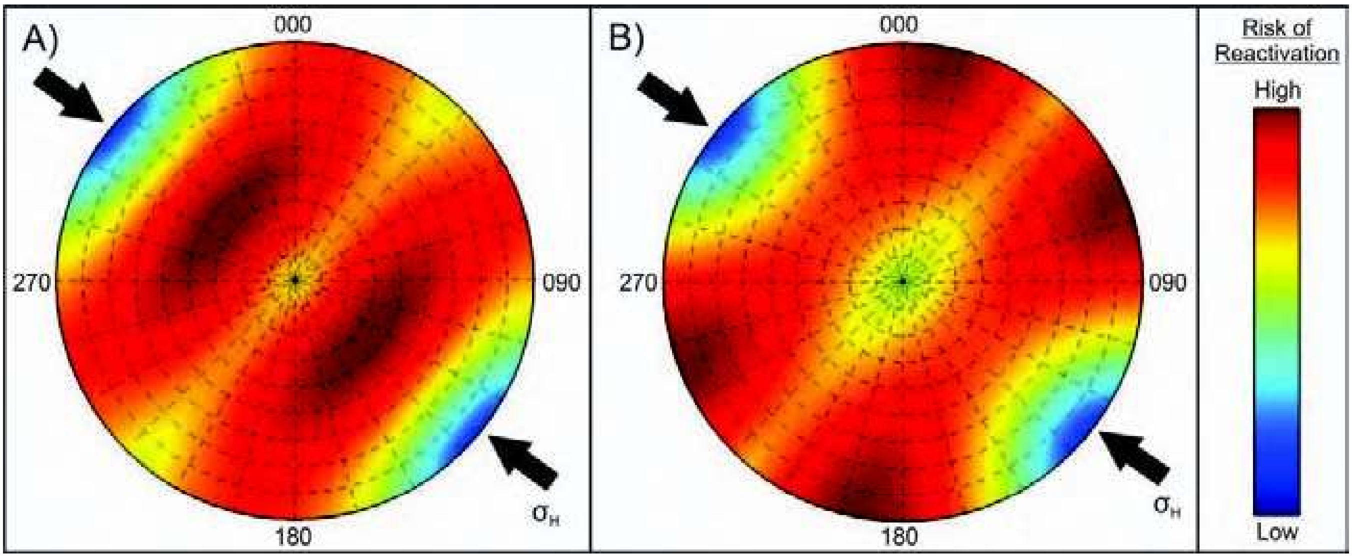

Figure 7. Fault reactivation diagrams illustrating the orientations of faults and fractures (plotted as poles to bedding) that are closer to the failure envelope and therefore, most likely to form or reactivate (red) in a (A) reverse fault stress regime and (B) a strike-slip fault stress regime. Proximity to the failure envelope requires a smaller increase in pore pressure to slide the Mohr circle into failure. Orientations of faults and fractures most likely to reactivate or form are coloured red and lie closest to failure on a Mohr circle. Orientations of faults and fractures least likely to reactivate or form are coloured blue and lie furthest from the failure envelope on a Mohr circle. Stress magnitudes are as follows; maximum principal stress is 40 MPa, intermediate principal stress is 20 MPa, and the minimum principal stress is 15 MPa.

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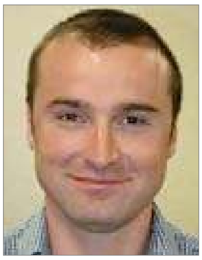

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