PRESENT-DAY STATE-OF-STRESS OF SOUTHEAST AUSTRALIA

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ABSTRACT

There have been several studies, both published and unpublished, of the present-day state-of-stress of southeast Australia that address a variety of geomechanical issues related to the petroleum industry. This paper combines present-day stress data from those studies with new data to provide an overview of the present-day state-of-stress from the Otway Basin to the Gippsland Basin. This overview provides valuable baseline data for further geomechanical studies in southeast Australia and helps explain the regional controls on the state-of-stress in the area.

Analysis of existing and new data from petroleum wells reveals broadly northwest–southeast oriented, maximum horizontal stress with an anticlockwise rotation of about 15° from the Otway Basin to the Gippsland Basin. A general increase in minimum horizontal stress magnitude from the Otway Basin towards the Gippsland Basin is also observed. The present-day state-of-stress has been interpreted as strike-slip in the South Australian (SA) Otway Basin, strike-slip trending towards reverse in the Victorian Otway Basin and borderline strike-slip/reverse in the Gippsland Basin. The present-day stress states and the orientation of the maximum horizontal stress are consistent with previously published earthquake focal mechanism solutions and the neotectonic record for the region. The consistency between measured present-day stress in the basement (from focal mechanism solutions) and the sedimentary basin cover (from petroleum well data) suggests a dominantly tectonic far-field control on the present-day stress distribution of southeast Australia. The rotation of the maximum horizontal stress and the increase in magnitude of the minimum horizontal stress from west to east across southeast Australia may be due to the relative proximity of the New Zealand segment of the plate boundary.

KEYWORDS

Southeast Australia, Gippsland Basin, Otway Basin, present-day stress, focal mechanism, neotectonics.

INTRODUCTION

To-date there is no coherent picture of the present-day state-of-stress in southeast (SE) Australia. Numerous papers have discussed the present-day state-of-stress of SE Australia either in the context of geomechanical applications to petroleum exploration and development (e.g. Hillis et al, 1995; Jones et al, 2000; Dewhurst et al, 2002) or in the context of neotectonics and the tectonic origin of the present-day stress field of the area (e.g. Dickinson et al, 2002; Sandiford et al, 2004). Information on the state-of-stress is spread throughout these published papers and other unpublished reports.

In the context of petroleum exploration and production, the present-day state-of-stress is significant, perhaps most notably for assessing the risk of fault reactivation (including the prediction of breached and live hydrocarbon columns) and to drilling-related issues such as wellbore stability. In the context of regional tectonics, knowledge of the present-day state-of-stress from petroleum data combined with earthquake focal mechanism solutions and the neotectonic record provide important insights into the structural and tectonic history of the region from the end-Miocene to the present-day. We have compiled published and unpublished data, and present new data, to provide the most comprehensive view possible of the present-day state-of-stress of SE Australia and to discuss the implications for neotectonics and the origin of stresses in the area.

Present-day stress data has been used to address a variety of petroleum exploration and development-related geomechanical issues in SE Australian basins including:

- fault reactivation and seal potential in the onshore SA Otway Basin (Penola Trough—Boult et al, 2002; Camac et al, 2004; Lyon et al, 2005);
- potential CO_2 sequestration sites in the onshore Victorian Otway Basin (Port Campbell embayment); and,
- wellbore stability/sand production and natural fracture-enhanced permeability in the offshore Gippsland Basin (Nelson and Hillis, 2005; Nelson et al, 2005), and potential CO2 sequestration sites in the offshore Gippsland Basin (Root et al, 2004).

It is not the intention of this paper to review in detail the geomechanical approach to the above issues, however, a short review of related literature follows.

Both palaeo- and live-hydrocarbon columns have been discovered in fault-dependent traps in the Penola Trough (SA Otway Basin—Lyon et al, 2005). Brittle failure of both fault and top seal have been investigated as possible seal-breaching mechanisms to explain the occurrence of palaeo-columns and to predict the likelihood of trap integrity (pre-drill).

- Hillis et al (1995) derived the first published present-day stress tensor (from four-arm caliper, leak-off tests and density/checkshot data) for the SA Otway Basin and summarised its implications for wellbore stability, water-flooding, naturally fractured reservoirs and fault trap integrity.

- Jones et al (2000) used knowledge of the orientation of seismic and sub-seismic faults and fractures within the present-day stress field to assess the risk of fault seal breach in the Otway Basin.
- Dewhurst et al (2002) determined failure envelopes (from triaxial testing) for well-lithified fault rocks in the Cooper Basin and applied their results to the risk of fault breach in the area.
- Boult et al (2002) and Camac (2004) proposed fracturing of intact top seal due to stress perturbations that occur locally around faults in the Penola Trough as a seal breaching mechanism.
- Lyon et al (2005) investigated the effects of fault reactivation, across fault juxtaposition and fault damage (e.g. shale gouge) on fault seal risk in the Penola Trough, concluding that the Pyrus fault had leaked due to reactivation within the present-day stress field.

The above references all provide some insight into the present-day state-of-stress in the SA Otway Basin, however, we have analysed new data for the SA Otway Basin to improve our knowledge of the present-day state-of-stress in the area.

The Victorian sector of the Otway Basin (Port Campbell embayment) is being considered as a possible CO_2 sequestration site. Leakage of CO_2 via faults and fractures (either pre-existing or newly formed) is a key risk that could allow CO_2 to escape its containment area and migrate into shallow aquifer systems or soil profiles. Accurate knowledge of present-day stress data is required to adequately assess the risk of fault/fracture reactivation and intact rock failure with injection of CO_2 (Root et al, 2004; Streit and Hillis, 2004). Although numerous petroleum wells have been drilled in both the onshore and offshore Victorian Otway Basin, no stress data have previously been published for the area.

Petroleum production began in earnest in the Gippsland Basin towards the end of 1969. Since then, more than 3.5 billion barrels of oil and five trillion cubic feet of gas have been produced from Eocene-aged structural closures (Shirley, 2004). As the shallower reservoirs become increasingly exhausted, deeper, less productive reservoirs are being considered for development. Fracture stimulation (onshore) and natural fracture-enhanced permeability (offshore) have been considered as means of making some of the deep, tight reservoirs commercial. Both fracture stimulation and natural fracture-enhanced permeability are strongly influenced by present-day stresses (Bell, 1996b; Sibson, 1996). The present-day stress tensor in the West Tuna area of the Gippsland Basin has previously been constrained by Nelson and Hillis (2005) and Nelson et al.(2005). However, additional previously unpublished stress data are available for the offshore Gippsland Basin and these are included herein.

In the following sections we discuss the magnitude of the vertical stress (S_v); the minimum horizontal stress (S_{hmin}); and the maximum horizontal stress (S_{Hmax}); and, the orientation of (S_{Hmax}) in the SA and Victorian Otway Basin and the Gippsland Basin. We then compare our present-day stress tensor from petroleum data with stress data from earthquake focal mechanism solutions and with the neotectonic record. Finally, the role that the New Zealand plate boundary plays on the magnitude and orientation of the present-day stress tensor in SE Australia is considered.

DETERMINING THE PRESENT-DAY STRESS TENSOR FROM PETROLEUM DATA

The S_{Hmax} orientation herein has been determined from borehole breakouts and drilling-induced tensile fractures (DITFs) interpreted from image logs and four-arm dipmeter logs (Zoback et al, 1985; Brudy, 1998; Brudy and Zoback, 1999). The azimuth of breakouts and DITFs may not directly reflect the orientation of the horizontal stresses in deviated wells (Mastin, 1988; Zoback et al, 1995). Only breakouts and DITFs observed in image logs from vertical to near-vertical (<15°) parts of the wellbore are considered herein. The vertical stress has been constrained by integration of the density log and use of check-shot and sonic log data from the surface to the top of the density log (Tingay et al, 2003; Nelson and Hillis, 2005). The minimum horizontal stress has been determined using leak-off tests and extended leak-off tests (Bell, 1996a; Gjønnes et al, 1998; Zoback et al, 2003). The S_{Hmax} magnitude has been constrained by the occurrence of DITFs and transverse drilling-induced tensile fractures (TDITFs) following Brudy (1998), Brudy and Zoback (1999) and Nelson et al.(2005). For simplicity, pore pressure in the Otway and Gippsland basins has been considered hydrostatic herein as is generally shown by pressure test data in the region. The Otway and Gippsland basins do contain some depleted reservoirs and overpressure does exist in the Gippsland Basin below 3,500 m and in some locations in the Bass Basin (e.g. the Pelican–5 well). As such, pore-pressures should be assessed in the reservoir of interest and the stress tensor presented herein modified accordingly prior to using it for practical applications in overpressured or depleted reservoirs.

IN SITU STRESS TENSOR—SA OTWAY BASIN

Maximum horizontal stress orientation

A total of 349 intervals of borehole breakout and 49 drilling-induced tensile fractures have been interpreted from eight image logs and four four-arm caliper logs from the SA Otway Basin (Table 1). Borehole breakouts were interpreted in 12 wells while four wells were interpreted to contain DITFs. New data interpreted herein has been combined with previously published data to determine the S_{Hmax} orientation in the SA Otway Basin (Table 2; Fig. 1). Only wells ranked A–C quality on the World Stress Map ranking scheme were considered to have a statistically significant average S_{Hmax} orientation (Zoback, 1992). D quality wells were not included in the statistical analysis and were not plotted on Figure 1. They have been recorded in Tables 1 and 2 to provide a complete list of all

Table 1. Image logs and four-arm dipmeter logs form the SA Otway interpreted as part of this study. BO refers to breakout. DITF refers to drilling-induced tensile fracture. Count relates to the number of BOs or DITFs interpreted in the well and SD s the standard deviation associated with the derived S_{Hmax} orientation.

Well	Basin	Location	Latitude	Longitude	S_{Hmax} Azimuth	Type	Log	Quality	Count	SD
Haselgrove–1	Otway (SA)	Onshore	-37.442	140.83	130	BO	four-arm caliper	A	18	3
Haselgrove South–2	Otway (SA)	Onshore	-37.462	140.876	145	BO	Image log	B	10	13
Hungerford–1	Otway (SA)	Onshore	-37.45	140.615	139	*BO	four-arm caliper	D	27	26
Jacaranda Ridge–1	Otway (SA)	Onshore	-37.35	140.753	131	BO	Image log	A	94	7
Katnook–4	Otway (SA)	Onshore	-37.455	140.776	126	BO	Image log	A	18	4
Killanoola–DW1	Otway (SA)	Onshore	-37.212	140.667	114	BO	Image log	A	31	4
Ladbroke Grove–2	Otway (SA)	Onshore	-37.465	140.791	132	BO	Image log	B	28	15
Ladbroke Grove–3	Otway (SA)	Onshore	-37.466	140.78	114	BO	Image log	A	69	9
Laira–1	Otway (SA)	Onshore	-37.426	140.675		BO	four-arm caliper	E		
Morum–1	Otway (SA)	Onshore	-37.502	139.235	155	BO	four-arm caliper	A	8	12
Redman–1	Otway (SA)	Onshore	-37.432	140.762	136	BO	four-arm caliper	D	27	31
Rendelsham–1	Otway (SA)	Onshore	-37.563	140.234	138	BO	four-arm caliper	A	12	12
Sophia Jane–1	Otway (SA)	Onshore	-37.313	139.617	105	BO	Image log	D	1	0
Wynn–1	Otway (SA)	Onshore	-37.409	140.872	121	BO	Image log	B	6	4
Haselgrove–1	Otway (SA)	Onshore	-37.442	140.83	131	DITF	Image log	A	13	6
Ladbroke Grove–2	Otway (SA)	Onshore	-37.465	140.791	146	DITF	Image log	D	2	4
Ladbroke Grove–3	Otway (SA)	Onshore	-37.466	140.78	119	DITF	Image log	A	21	5
Wynn–1	Otway (SA)	Onshore	-37.409	140.872	127	DITF	Image log	D	3	4

wells analysed as part of this study. The contrast between previously published and new data interpreted for this study can be seen in Figures 2 and 3. The average S_{Hmax} orientation derived from the interpreted (A–C quality) breakouts is ~125° north (Fig. 1). The standard deviation of breakout orientation from all breakouts interpreted in the nine wells is 13.3°. The average S_{Hmax} orientation derived from the interpreted (A–C quality) DITFs is ~124° north and is very consistent with the breakout data (Fig. 1). The standard deviation of all DITF orientations interpreted in the two wells is 7.9°.

The S_{Hmax} orientation of ~125° north determined herein compares well with previous work by Hillis et al, (1995) and Lyon et al, (2005). They determined that S_{Hmax} is oriented ~125° north from analysis of four-arm calliper data from 11 wells, and 128° north from analysis of borehole breakout in image logs from eight wells respectively (Table 2).

Vertical stress magnitude

Vertical stress profiles have been determined for 13 onshore wells and four offshore wells from the SA Otway Basin (Table 3; Fig. 4). The onshore vertical stress gradients are calculated relative to ground level and offshore wells relative to seabed. Vertical stress profiles were calculated relative to seabed in order to remove the effect of the varying water depth. The vertical stress at any particular depth calculated relative to seabed can be converted to relative to mean-sea-level by adding the vertical stress component due to the water column.

The vertical stress calculated in the onshore SA Otway Basin is reasonably consistent and varies from 20 MPa at 1 km depth to 67.5 MPa/km at 3 km depth (Fig. 4a). The vertical stress determined offshore shows slight variation in magnitude at depth (Fig. 4b). There is no discernable geographic/geological pattern in the variation of the offshore vertical stress. The offshore wells were spaced at considerable distance from each other (Fig. 5). It is possible that lateral variability of rock units and hence density accounts for some of the slight variation in S_v with depth. The vertical stress ranges from approximately 20 MPa at 1km depth to between 63 MPa (Argonaut) and 66 MPa (Crayfish) at 3 km depth in the offshore wells. The variability of S_v across the SA Otway Basin is low in a global context and is best described with a power law function of the form

$$\sigma_v = 21.182Z^{1.0555} \qquad 1.$$

where Z is the depth to the reservoir of interest expressed in kilometres.

Minimum horizontal stress magnitude

The minimum horizontal stress has been calculated from 13 reported leak-off tests (RLOTs) and two extended leak-off tests conducted in the SA Otway Basin (Table 4; Figs 5 and 6). The reported leak-off pressures were recorded in daily-drilling reports from well completion reports. The pressure/volume pumped records were not available for the RLOTs and hence their reliability/quality could not be assessed. Extended leak-off tests are considered very reli-

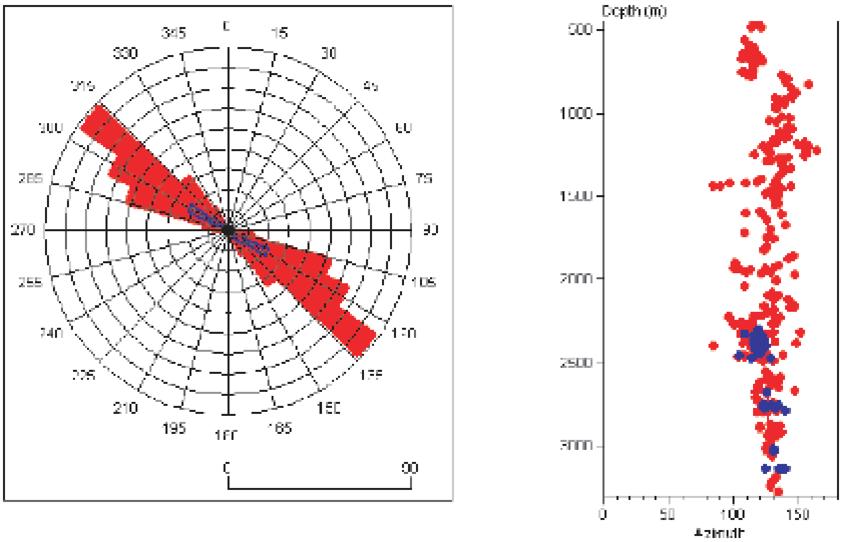


Figure 1. Rose plot of S_{Hmax} orientation (left) and depth plot of S_{Hmax} orientation (right) based on the interpretation of 359 A-C quality breakouts (red data) and 34 A-C quality DITFs (blue data) interpreted in the SA Otway Basin.

able estimates of minimum horizontal stress (Bell, 1996a). Closure pressures determined from the extended leak-off tests (thick red trendline in Fig. 6) are very consistent with the leak-off pressures reported in the well completion reports (thin red trendline in Fig. 6). The extended leak-off and reported leak-off pressures suggest the minimum horizontal stress is ~15.5 MPa/km in the South Australian sector of the Otway Basin.

Maximum horizontal stress magnitude

The vertical and minimum horizontal stress magnitudes calculated herein are laterally consistent across the SA Otway Basin. Drilling-induced tensile fractures were observed in four of the eight image logs interpreted in the SA Otway Basin. The consistent present-day stress magnitude across it and the occurrence of DITFs allows a regional S_{Hmax} magnitude to be determined. The presence of DITFs in (near vertical) wells requires a large difference between the minimum and maximum horizontal stress (Barton et al, 1998). In using DITFs to constrain S_{Hmax} we follow Brudy and Zoback (1999) and conservatively assume that the tensile strength of the reservoir rock is negligible. This constrains a lower bound estimate for the maximum horizontal stress. The occurrence of DITFs and knowledge of the other stress components above constrain the S_{Hmax} magnitude to about 29 MPa/km. Analysis of the present-day stress tensor herein suggests a strike-slip state-of-stress in the SA Otway Basin (i.e. $S_{Hmax}>S_v>S_{hmin}$).

Table 2. Previously published four-arm dipmeter data from the SA Otway Basin (Hillis et al, 1995). BO refers to breakout. DITF refers to drilling-induced tensile fracture. Count relates to the number of BOs or DITFs interpreted in the well and SD is the standard deviation associated with the derived S_{Hmax} orientation.

Well	Basin	Location	Latitude	Longitude	S_{Hmax} Azimuth	Type	Log	Quality	Count	SD
Break Sea Reef–1	Otway (SA)	Offshore	-38.159	140.612	118	BO	four-arm caliper	D	67	43
Greenways–1	Otway (SA)	Onshore	-37.228	140.161	116	BO	four-arm caliper	D	5	33
Hatherleigh–1	Otway (SA)	Onshore	-37.486	140.253		BO	four-arm caliper	E		
Katnook–1	Otway (SA)	Onshore	-37.454	140.781	119	BO	four-arm caliper	C	34	22
Katnook–2	Otway (SA)	Onshore	-37.451	140.789	13	BO	four-arm caliper	E	11	46
Katnook–3	Otway (SA)	Onshore	-37.45	140.774	164	BO	four-arm caliper	D	27	35¥
Ladbroke Grove–1	Otway (SA)	Onshore	-37.468	140.781	119	BO	four-arm caliper	C	31	23
Reedy Creek–1	Otway (SA)	Onshore	-37.323	140.155		BO	four-arm caliper	E		
Sawpi–1	Otway (SA)	Onshore	-38.349	140.873	121	BO	four-arm caliper	E	8	50
St. Clair–1	Otway (SA)	Onshore	-37.404	140.033	143	BO	four-arm caliper	D	6	34
Zema–1	Otway (SA)	Onshore	-37.414	140.666	131	BO	four-arm caliper	D	48	28

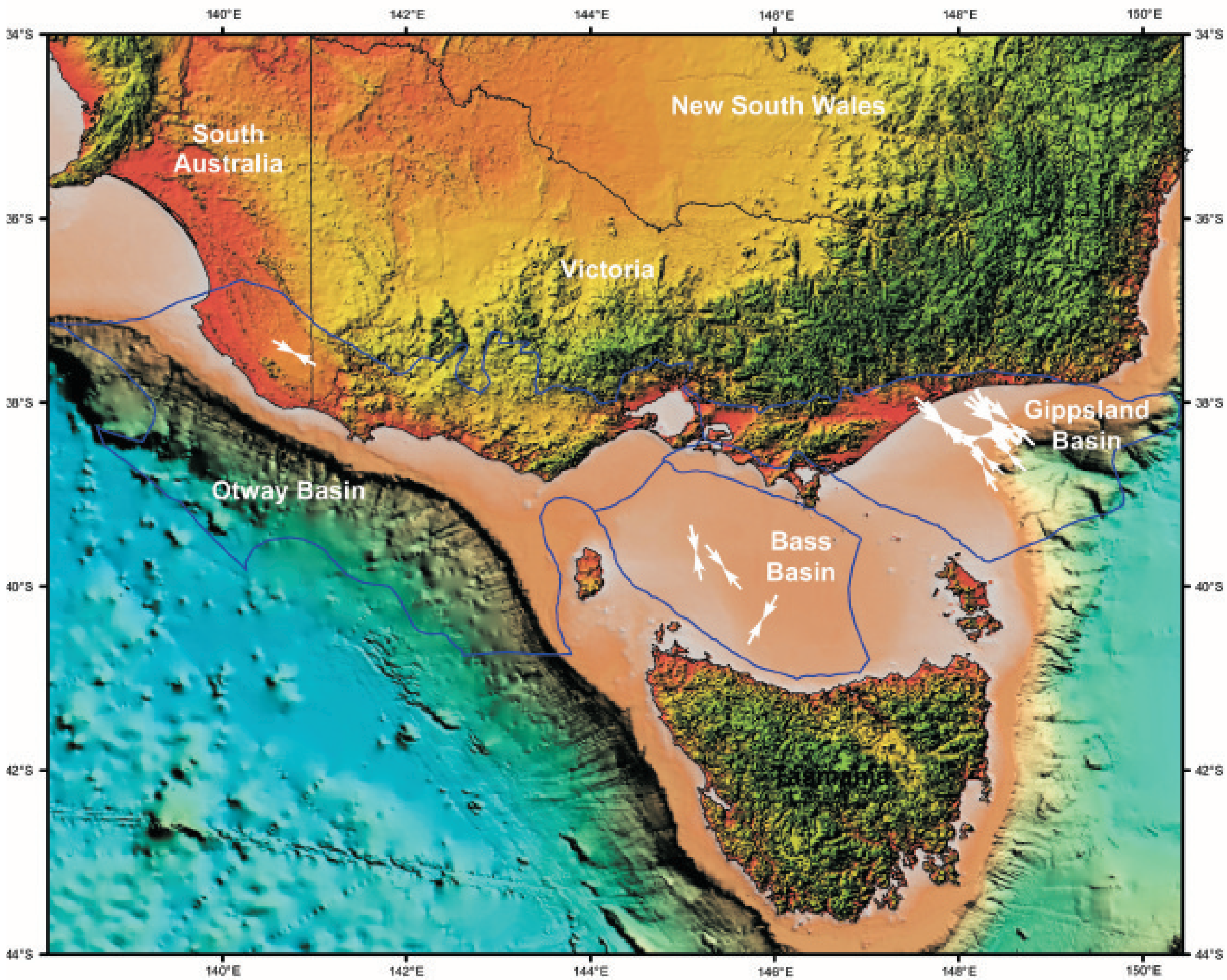


Figure 2. Previously published S_{Hmax} orientations from SE Australia. The arrows represent S_{Hmax} orientations derived from breakout data. The blue outlines show the boundaries of the Otway, Bass and Gippsland basins.

PRESENT-DAY STRESS TENSOR—VICTORIAN OTWAY BASIN

Maximum horizontal stress orientation

No present-day stress orientation or magnitude data was publicly available for the Victorian Otway Basin prior to this study (Fig. 2). A total of 36 intervals of borehole breakout and 53 drilling-induced tensile fractures have been interpreted from four image logs in the Victorian Otway Basin (Table 5). Borehole breakouts were interpreted in three logs while two logs were interpreted to contain DITFs. The image logs for Minerva–1 and Minerva–2a exhibit borehole breakout through the entire logged interval. The image logs were from the FMS tool and the percentage of the wellbore imaged was low. The image tools did not rotate as they were drawn up the well and the tool's pads were interpreted not to have stuck in the true breakout orientation. In addition to the

Table 3. Vertical stress profiles calculated in the SA Otway Basin

Well	Basin	Location	Latitude	Longitude
Argonaut–1A	Otway (SA)	Offshore	-37.97012	140.2661
Chama–1A	Otway (SA)	Offshore	-37.42546	139.5449
Copa–1	Otway (SA)	Offshore	-37.68695	139.7575
Crayfish–1	Otway (SA)	Offshore	-37.28944	139.5972
Katnook–2	Otway (SA)	Onshore	-37.44948	140.7897
Ladbroke Grove–1	Otway (SA)	Onshore	-37.46711	140.7822
Digby–1	Otway (SA)	Onshore	-37.8461	141.5032
Hungerford–1	Otway (SA)	Onshore	-37.4504	140.5982
Laira-1	Otway (SA)	Onshore	-37.4267	140.6733
Viewbank–1	Otway (SA)	Onshore	-37.3269	140.7577
Katnook–1	Otway (SA)	Onshore	-37.4533	140.7817
Ladbroke Grove–3	Otway (SA)	Onshore	-37.4656	140.7804
Wynn–1	Otway (SA)	Onshore	-37.4092	140.8722

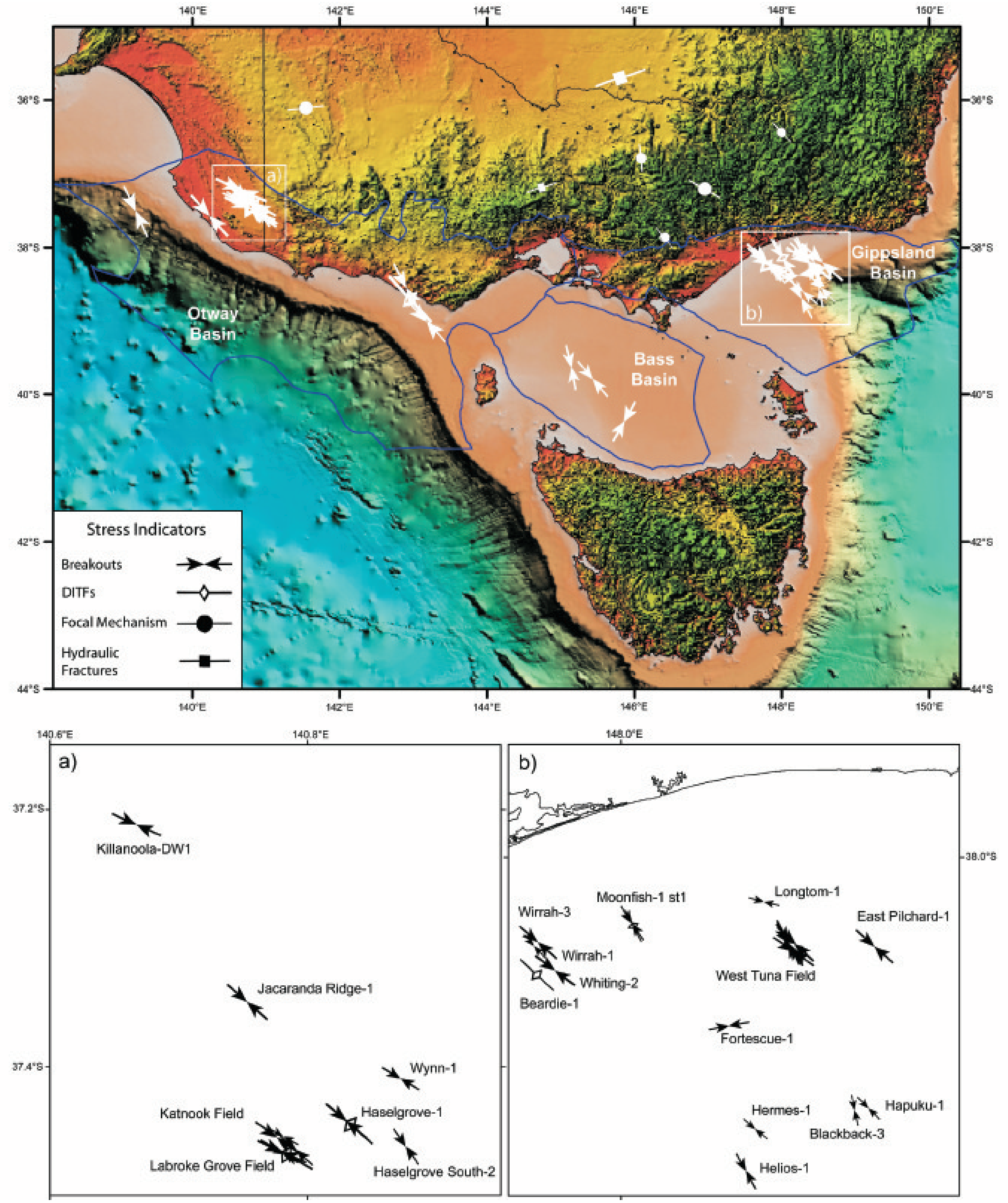


Figure 3. S_{Hmax} orientation data derived from image log and 4-arm dipmeter data in this study. The S_{Hmax} orientations from A–C quality focal mechanisms from the Australian Stress Map are also shown. The Penola trough (a) and Gippsland Basin (b) have been magnified to show the individual stress orientation arrows.

problems with the Minerva image logs, only a paper image log was available for interpreting wellbore failure in Dunbar–1. Drilling-induced tensile fractures interpreted in the Minerva image logs were considered a more reliable indication of the S_{Hmax} orientation than that derived from borehole breakout. The S_{Hmax} orientation derived from DITFs in the Victorian Otway Basin was 137° north (Fig. 7). The standard deviation of all DITF orientations interpreted in the two wells is 7.0°. An A-quality interpretation of S_{Hmax} orientation from breakouts interpreted on the Eric-the-Red image log similarly indicated that the S_{Hmax} orientation is ~135° north in the Victorian Otway Basin (Table 5).

Vertical stress magnitude

Vertical stress profiles have been determined for five onshore and five offshore wells from the Victorian Otway Basin (Table 6; Fig. 8). As in the SA Otway Basin the onshore vertical stress gradients are calculated relative to ground-level and the offshore wells relative to seabed. The vertical stress determined onshore in the Victorian Otway is reasonably consistent. The vertical stress offshore shows a slight variation in magnitude at depth (1 MPa/km at 3 km). None of the offshore density logs available contained shallow data (density points close to the sea-bed). As such the offshore vertical stress profiles are much less well constrained than the onshore profiles. Furthermore, significant breakout was observed in the offshore wells, which has affected density log quality. Despite these difficulties with the offshore S_v determination, both the onshore and offshore vertical stress profiles show that the vertical stress ranges from ~20 MPa at 1 km depth to ~42.5 MPa at 2 km depth. Power law functions most accurately approximate the vertical stress in the Victorian Otway Basin and have the form

$$\sigma_v = 20.044Z^{1.0788} \qquad 2.$$

where Z is the depth to the reservoir of interest expressed in kilometres.

Minimum horizontal stress magnitude

The minimum horizontal stress magnitude in the Victorian Otway Basin has been determined from 16 reported

Table 4. Extended leak-off pressures (XLOTs) and reported leak-off pressures (RLOTs) from wells in the South Australian Otway.

Well	Basin	Location	Latitude	Longitude	Depth (m)	Pressure (MPa)	Test type
Balnaves–1	Otway (SA)	Onshore	37.45	140.70	860.00	13.40	XLOT
Camelback–1	Otway (SA)	Onshore	37.10	140.19	289.90	5.32	RLOT
Compton–1	Otway (SA)	Onshore	37.79	140.71	479.50	8.96	RLOT
Haselgrove–1	Otway (SA)	Onshore	37.44	140.83	888.00	13.36	RLOT
Haselgrove–2	Otway (SA)	Onshore	37.45	140.84	818.00	14.78	RLOT
Hungerford–1	Otway (SA)	Onshore	37.45	140.60	942.00	13.55	RLOT
Killarney–1	Otway (SA)	Onshore	37.10	140.31	267.90	3.56	RLOT
Ladbroke Grove–3	Otway (SA)	Onshore	37.46	140.82	820.00	12.60	XLOT
Lake Hawdon–1	Otway (SA)	Onshore	37.20	139.99	392.90	7.67	RLOT
Mount Hope	Otway (SA)	Onshore	37.50	140.09	124.80	2.89	RLOT
Rendelsham–1	Otway (SA)	Onshore	37.56	140.23	1104.90	16.78	RLOT
St Clair–1	Otway (SA)	Onshore	37.36	140.04	1704.60	25.05	RLOT
Tilbooroo–1	Otway (SA)	Onshore	37.33	140.87	1549.00	27.02	RLOT
Tilbooroo-1	Otway (SA)	Onshore	37.33	140.87	347.32	4.90	RLOT
Wynn-1	Otway (SA)	Onshore	37.41	140.87	882.20	13.43	RLOT

Table 5. Image logs from the Victorian Otway interpreted as part of this study. BO refers to breakout. DITF refers to drilling-induced tensile fracture. Count relates to the number of BOs or DITFs interpreted in the well and SD is the standard deviation associated with the derived S_{Hmax} orientation.

Well	Basin	Location	Latitude	Longitude	S_{Hmax} Azimuth (N)	Type	Log	Quality	Count	SD
Minerva–1	Otway (Vic)	Offshore	-38.703	142.953	137.11	DITF	Image log	A	36	8
Minerva–1	Otway (Vic)	Offshore	-38.703	142.953	142	BO	Image log	D	1	
Minerva–2a	Otway (Vic)	Offshore	-38.718	142.956	138.12	DITF	Image log	A	17	2
Minerva–2a	Otway (Vic)	Offshore	-38.718	142.956	144	BO	Image log	D	1	
Ericthered–1	Otway (Vic)	Offshore	-39.011	143.182	137	BO	Image log	A	18	11
Dunbar–1	Otway (Vic)	Onshore	-38.548	142.907	151	BO	Image log	A (?)	16	6

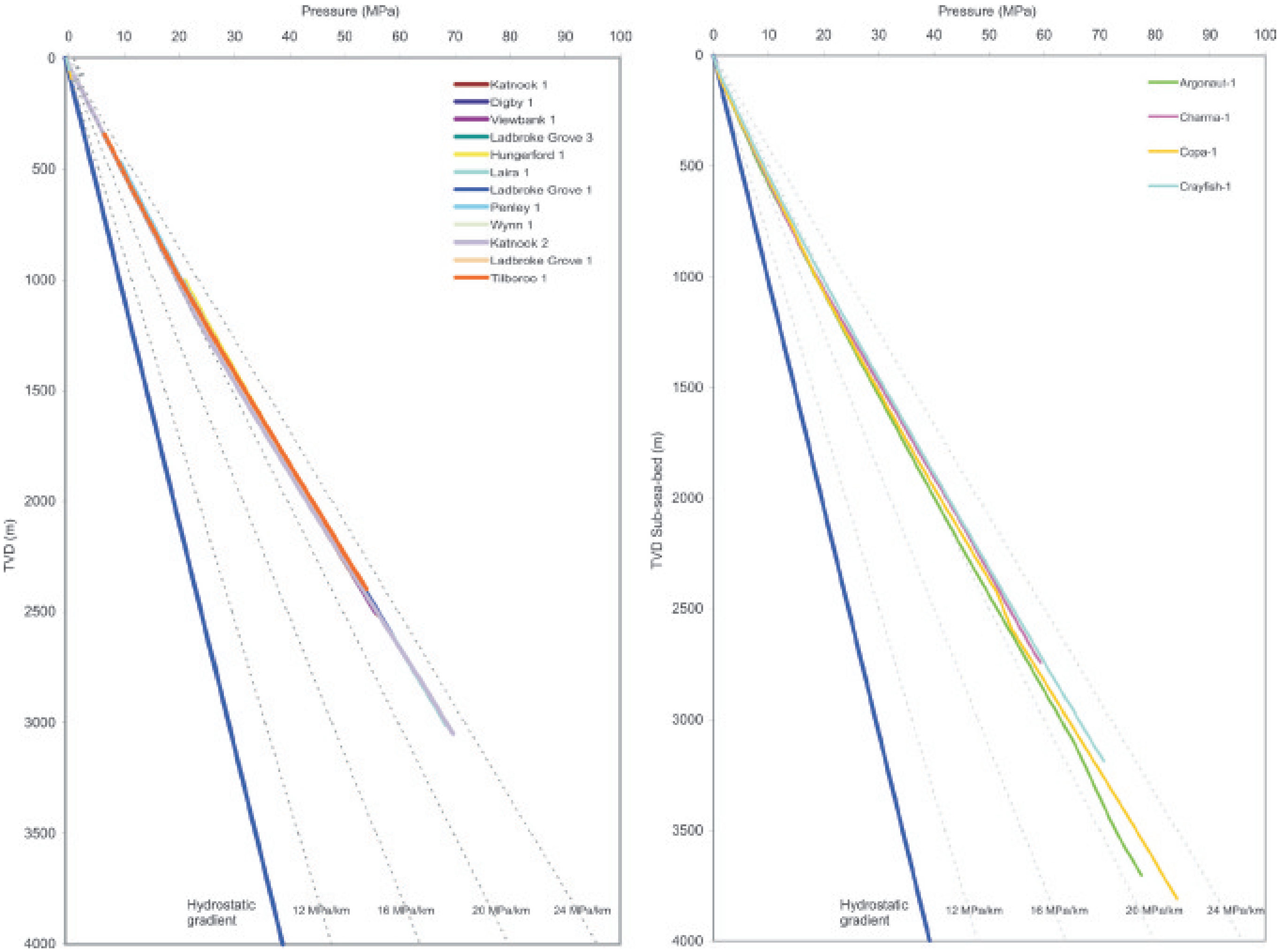


Figure 4. Vertical stress profiles from the onshore SA Otway Basin (left) and the offshore SA Otway Basin (right).

leak-off pressures recorded in daily-drilling reports and 16 leak-off tests for which pressure/volume pumped records were available (Table 7; Fig. 6). The leak-off pressures determined from the pressure/volume pumped records (dark green line, Fig. 6) are very consistent with the leak-off pressures reported in the well completion reports (light green line, Fig 6). The RLOTs and LOTs indicate that the magnitude of the minimum horizontal stress is ~18.5 MPa/km. It is interesting to note that the minimum stress magnitude is higher in the Victorian Otway Basin than in the SA Otway Basin.

Maximum horizontal stress magnitude

The vertical and minimum stress magnitudes determined above appear to be laterally consistent across the Victorian Otway Basin. Drilling-induced tensile fractures were observed in two of the four image logs interpreted in the Victorian Otway Basin. The occurrence of DITFs, knowledge of the S_{hmin} and S_v magnitudes (as determined above) and the assumption that the tensile strength of the reservoir rocks are negligible allow us to constrain the S_{Hmax} magnitude to about 37 MPa/km in the Victorian Otway Basin (as discussed for the SA Otway Basin). The present-day stress tensor derived from petroleum well data herein

Table 6. Vertical stress profiles calculated in the Victorian Otway Basin.

Well	Basin	Location	Latitude	Longitude
Rowans–1	Otway (Vic)	Onshore	-38.45968	142.7887
Boggy Creek–1	Otway (Vic)	Onshore	-38.526	142.824
Curdievale–1	Otway (Vic)	Onshore	-38.55528	142.7839
Wallaby Creek–1	Otway (Vic)	Onshore	-38.57139	142.9053
Barton Corner	Otway (Vic)	Onshore	-38.4314	142.755
Eric the Red–1	Otway (Vic)	Offshore	-39.0111	143.1823
Loch Ard–1	Otway (Vic)	Offshore	-38.9304	143.1834
Minerva–1	Otway (Vic)	Offshore	-38.7019	142.9548
Minerva–2	Otway (Vic)	Offshore	-38.7163	142.9568
Discovery Bay–1	Otway (Vic)	Offshore	-38.4119	141.0725

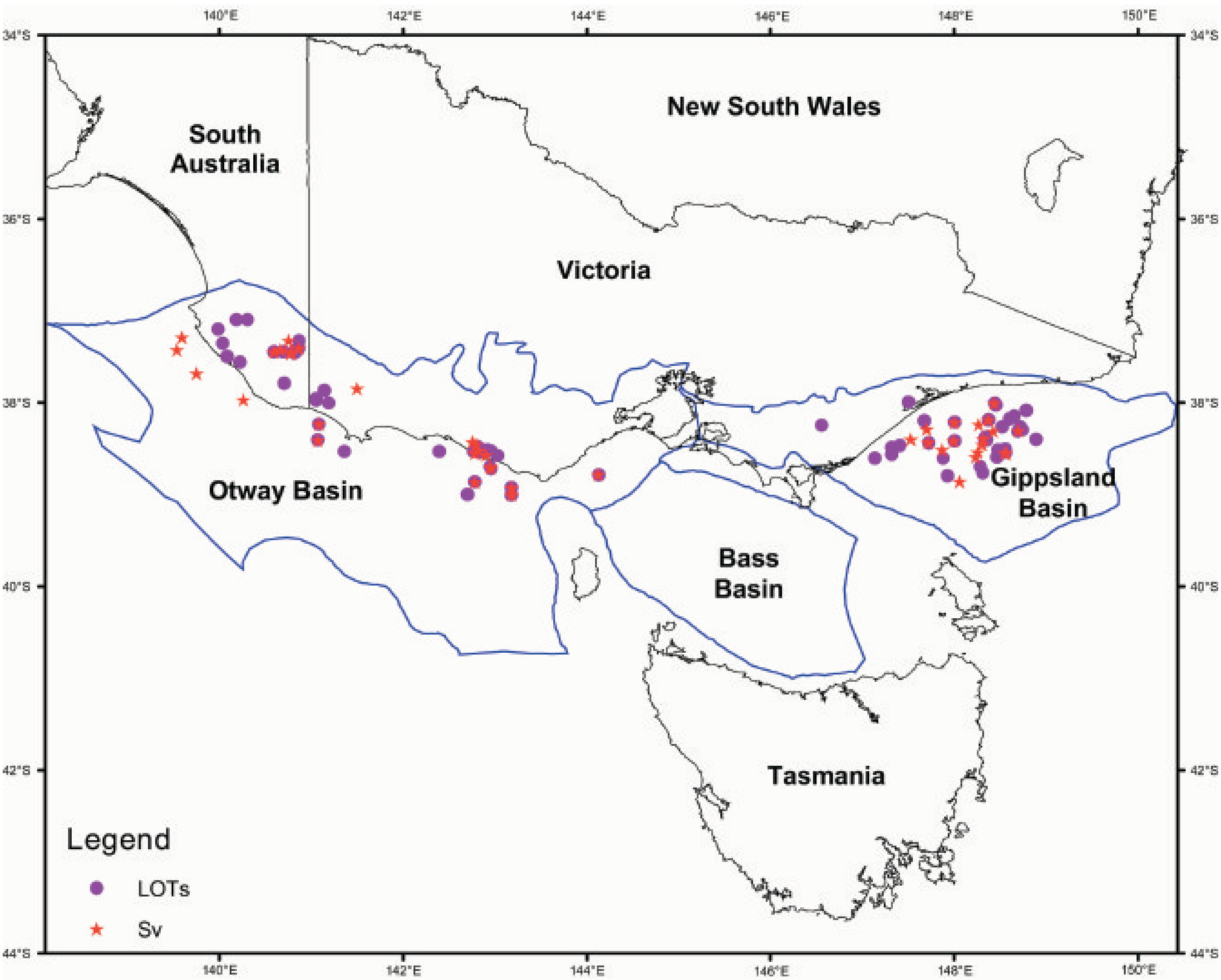


Figure 5. Location map showing the lateral spread of wells in which vertical stress profiles were calculated (stars) and the leak-off tests (dots) which were used to constrain the S_{hmin} magnitude.

suggests that the Victorian sector of the Otway Basin is in a strike-slip stress state (i.e. $S_{Hmax}>S_v>S_{hmin}$). However, the high magnitude of S_{hmin} (compared to the SA sector of the Otway Basin) derived from leak-off tests suggests that the stress regime is approaching a reverse stress regime (i.e. $S_{Hmax}>S_{hmin}>S_v$) and also suggests that the differential stress is higher than observed in the SA Otway Basin.

PRESENT-DAY STRESS TENSOR—BASS BASIN

Unfortunately, no new present-day stress magnitude or orientation data was available in the Bass Basin for this study. Table 8 shows only the A–C quality stress data previously available from the Australian stress map project (Hillis et al, 1998; Hillis and Reynolds, 2003). The three available data-points are from four-arm dipmeter logs and show considerable scatter (Figs 2 and 3). We believe that more data, especially from image logs, is required before the state-of-stress in the Bass Basin can be resolved.

PRESENT-DAY STRESS TENSOR—GIPPSLAND BASIN

Maximum horizontal stress orientation

The regional S_{Hmax} orientation in the Gippsland Basin has been determined from previously published data (Hillis and Reynolds, 2003; Nelson and Hillis, 2005) and from breakout and DITFs observed on image logs interpreted as part of this study (Tables 9 and 10). As was the case in the Otway Basin above, only wells ranked A–C quality on the World Stress Map ranking scheme were considered to have a statistically significant average S_{Hmax} orientation (Zoback, 1992). The average S_{Hmax} orientation derived from the 118 (A–C quality) breakouts in 11 wells across the Gippsland Basin is ~139° north (Figs 3 and 9). The standard deviation of all interpreted breakout orientations is 15.1°. The average S_{Hmax} orientation derived from the 16 interpreted

Table 7. Leak-off pressures (LOTs) and reported leak-off pressures (RLOTs) from wells in the Victorian Otway.

Well	Basin	Location	Latitude	Longitude	Depth (m)	Pressure (MPa)	Test type
Boggy Creek–1	Otway (Vic)	Onshore	-38.53	142.82	288.05	5.17	RLOT
Bridgewater Bay–1	Otway (Vic)	Offshore	-38.54	141.36	471.00	6.69	RLOT
Bridgewater Bay–1	Otway (Vic)	Offshore	-38.54	141.36	1573.00	24.00	RLOT
Bridgewater Bay–1	Otway (Vic)	Offshore	-38.54	141.36	3498.00	69.82	RLOT
Champion–1	Otway (Vic)	Offshore	-38.54	142.39	1191.00	22.40	LOT
Conan–1	Otway (Vic)	Offshore	-38.87	142.78	1175.00	23.07	LOT
Croft–1	Otway (Vic)	Onshore	-38.54	142.77	466.30	4.01	LOT
Curdie–1	Otway (Vic)	Onshore	-38.55	142.82	121.20	2.30	RLOT
Discovery Bay–1	Otway (Vic)	Offshore	-38.41	141.07	400.10	4.98	RLOT
Discovery Bay–1	Otway (Vic)	Offshore	-38.41	141.07	1176.40	16.70	RLOT
Eric the Red–1	Otway (Vic)	Offshore	-39.01	143.18	329.70	4.01	LOT
Eric the Red–1	Otway (Vic)	Offshore	-39.01	143.18	981.70	18.76	LOT
Fahley–1	Otway (Vic)	Onshore	-37.96	141.05	50.10	0.85	RLOT
Fahley–1	Otway (Vic)	Onshore	-37.96	141.05	918.10	15.85	RLOT
Fahley–2	Otway (Vic)	Onshore	-37.98	141.05	262.60	3.70	RLOT
Henke–1	Otway (Vic)	Onshore	-38.01	141.19	258.90	3.65	RLOT
Iona–1	Otway (Vic)	Onshore	-38.58	143.03	115.60	2.20	RLOT
La Bella–1	Otway (Vic)	Offshore	-39.00	142.70	1760.70	34.51	LOT
Lavers–1	Otway (Vic)	Onshore	-38.48	142.80	420.31	8.83	LOT
Loch Ard–1	Otway (Vic)	Offshore	-38.93	143.18	356.70	5.03	LOT
McIntee–1	Otway (Vic)	Onshore	-38.49	142.82	423.24	7.98	LOT
Minerva–1	Otway (Vic)	Offshore	-38.70	142.95	1163.70	22.12	LOT
Minerva–1	Otway (Vic)	Offshore	-38.70	142.95	2077.70	37.67	LOT
Minerva–2	Otway (Vic)	Offshore	-38.72	142.96	1500.70	25.74	LOT
Naylor–1	Otway (Vic)	Onshore	-38.53	142.81	480.25	9.48	LOT
Normanby–1	Otway (Vic)	Offshore	-38.24	141.08	639.20	8.21	RLOT
Normanby–1	Otway (Vic)	Offshore	-38.24	141.08	1528.20	19.62	RLOT
Normanby–1	Otway (Vic)	Offshore	-38.24	141.08	2663.20	50.11	RLOT
Penryn–1	Otway (Vic)	Onshore	-38.53	142.96	665.56	11.82	LOT
Squatter–1	Otway (Vic)	Onshore	-37.87	141.14	265.30	3.74	RLOT
Tregony–1	Otway (Vic)	Onshore	-38.52	142.92	372.95	6.78	LOT
Wild Dog–1	Otway (Vic)	Offshore	-38.79	144.13	297.70	4.76	LOT
Wild Dog–1	Otway (Vic)	Offshore	-38.79	144.13	715.70	11.50	LOT

(A–C quality) DITFs from two wells is ~140°N (Fig. 9). The standard deviation of all (A–C quality) interpreted DITF orientations is 11.5°.

The S_{Hmax} orientation of ~139° north derived herein is consistent with the previous orientation of 138° north determined in the West Tuna area of the Gippsland Basin (Nelson and Hillis, 2005). The orientation varies slightly from the orientation of 130° north published in the Australian Stress Map (ASM; Hillis et al, 1998; Hillis and Reynolds, 2003). Previous determinations of maximum horizontal stress recorded in the ASM were based on four-arm dipmeter logs from seven wells in the Gippsland Basin. Breakout interpretation from four-arm dipmeter logs is much less reliable than interpretation from image logs, as evidenced in the scatter of orientations listed in Table 9 (see also Brudy and Kjorholt, 2001). Furthermore, the older dipmeter data was inherited when the Australian Stress Map took over the World Stress Map database for the region and the origin is unknown. The dipmeter logs have not been accessed by the authors and the quality of the interpretation could not be assessed.

Vertical stress magnitude

The vertical stress magnitude has been constrained in 18 wells located in the offshore Gippsland Basin (Table 11; Fig. 10). The vertical stress profiles have been presented relative to sea-bed to remove the effect of water depth, which varies from ~20 m to over 400 m depending on well location. A significant number of coal beds occur throughout the Gippsland Basin. These can cause problems in calculating vertical stress because they are often associated with poor hole conditions. Ignoring coals by systematically removing data in intervals with poor hole

Table 8. Previously published four-arm dipmeter data from the Bass Basin (from Hillis and Reynolds, 2003).

Well	Basin	Location	Latitude	Longitude	S_{Hmax} Azimuth (ºN)	Type	Log	Quality	Count	SD
Dolphin mine	Bass	King Island	-40.04	144.05	159	OC		D	1	0
Aroo–1	Bass	Offshore	-39.792	145.448	140	BO	four-arm caliper	B	3	15
Koorkah–1	Bass	Offshore	-39.633	145.151	168	BO	four-arm caliper	B	21	20
Nangkero–1	Bass	Offshore	-40.074	145.978	126	BO	four-arm caliper	D	1	0
Pelican–3	Bass	Offshore	-40.262	145.864	2	BO	four-arm caliper	D	2	26
Pelican–4	Bass	Offshore	-40.361	145.872	29	BO	four-arm caliper	B	8	9
Pelican–5	Bass	Offshore	-40.345	145.864	123	BO	four-arm caliper	D	10	40
Pipipa–1	Bass	Offshore	-40.386	145.696	82	BO	four-arm caliper	D	1	0
Poonboon–1	Bass	Offshore	-40.138	145.917	151	BO	four-arm caliper	D	3	13
Tilana–1	Bass	Offshore	-39.894	145.978	74	BO	four-arm caliper	D	1	0
Toolka–1	Bass	Offshore	-39.41	145.396	18	BO	four-arm caliper	D	6	27
Yurongi–1	Bass	Offshore	-39.921	146.267	44	BO	four-arm caliper	D	3	19
Yolla–1	Bass	Offshore	-39.839	145.806	134	BO	four-arm caliper	D	12	31

quality can lead to higher sediment density and vertical stress because the coal sections have low density. Coals were identified by their combined sonic, gamma ray and density response following Nelson and Hillis (2005).

The offshore Gippsland Basin vertical stress profiles do appear to vary slightly. The cause of this variation is unclear however, the vertical stress has been sampled over quite a large lateral area and variable thicknesses of some units (for example the Latrobe Group coals or 'Sea-Spray' group carbonates) may affect the density profile and hence the vertical stress gradient. The vertical stress ranges from ~20 MPa at 1 km depth to ~68 MPa (+/- 3MPa) at 3 km depth. Despite the variation in vertical stress it can be reasonably described by the power law function

$$\sigma_v = 20.979Z^{1.0673} \qquad 3.$$

(+/- 3MPa at 3 km depth) where Z is the depth of the reservoir of interest expressed in kilometres sub-sea.

Minimum horizontal stress magnitude

The minimum horizontal stress magnitude has been determined from 34 'reported' leak-off pressures recorded in daily-drilling reports and five leak-off tests for which pressure/volume pumped records were available (Table 12; Fig. 6). The leak-off pressures determined from the pressure/volume pumped records (dark blue line in Fig. 6) are very consistent with the leak-off pressures reported in the well completion reports (light blue line in Figure 6). The leak-off test data indicates that the minimum horizontal stress is ~20 MPa/km in the Victorian Otway Basin. Analysis of the minimum horizontal stress from the SA Otway Basin through the Victorian Otway Basin to the Gippsland Basin suggests a broad increase in stress from west to east.

Maximum horizontal stress magnitude

Drilling-induced tensile fractures were observed in

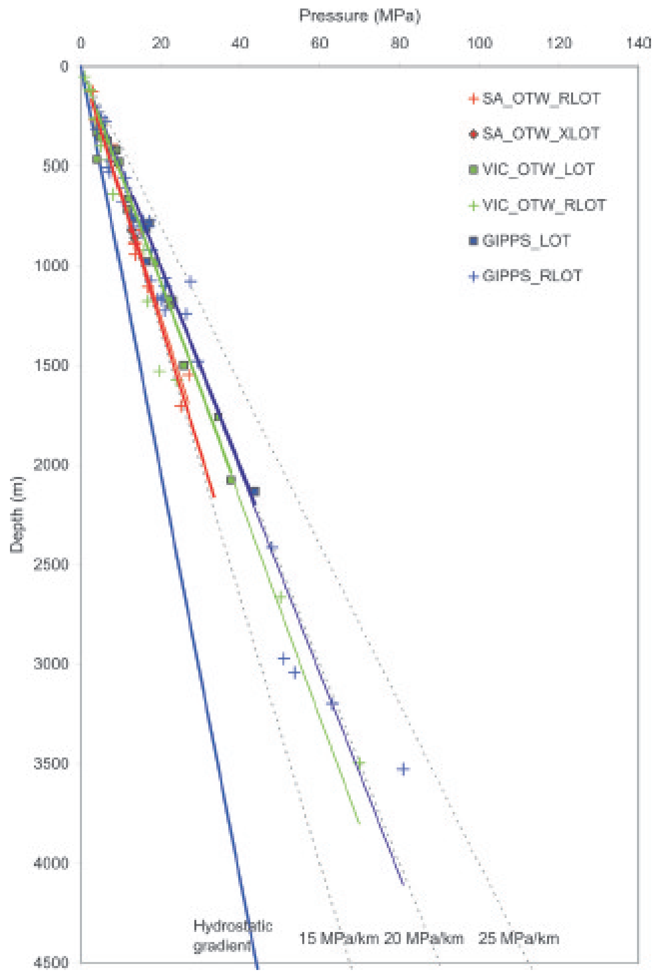


Figure 6. Minimum horizontal stress magnitude gradients determined from LOTs, XLOTs and RLOTs for the SA Otway Basin (red), Victorian Otway Basin (green) and Gippsland Basin (blue).

Table 9. Previously published S_{Hmax} orientations derived from image logs and four-arm caliper logs from the Gippsland Basin (Hillis and Reynolds, 2003; Nelson and Hillis, 2005). BO refers to breakout. DITF refers to drilling-induced tensile fracture. Count relates to the number of BOs or DITFs interpreted in the well and SD is the standard deviation associated with the derived S_{Hmax} orientation.

Well	Basin	Location	Latitude	Longitude	S_{Hmax} Azimuth (ºN)	Type	Log	Quality	Count	SD
Aroo-1	Bass	Offshore	-39.792	145.448	140	BO	four-arm caliper	B	3	15
Flounder-1	Gippsland	Offshore	-38.319	148.436	122	BOC	four-arm caliper	D	5	2
Hapuku-1	Gippsland	Offshore	-38.555	148.549	135	BOC	four-arm caliper	C	6	19
Fortescue-1	Gippsland	Offshore	-38.374	148.239	80	BO	four-arm caliper	B	5	15
Whiting-2	Gippsland	Offshore	-38.251	147.854	127	BO	four-arm caliper	A	18	12
Selene-1	Gippsland	Offshore	-38.437	148.437	123	BOC	four-arm caliper	D	1	0
Omeo-1	Gippsland	Offshore	-38.613	147.717	116	BO	four-arm caliper	D	3	4
Hermes-1	Gippsland	Offshore	-38.602	148.298	130	BOC	four-arm caliper	C	4	9
Helios-1	Gippsland	Offshore	-38.695	148.276	151	BOC	four-arm caliper	B	7	13
Wirrah-3	Gippsland	Offshore	-38.197	147.808	138	BOC	four-arm caliper	C	3	2
Wirrah-1	Gippsland	Offshore	-38.189	147.816	131	BO	four-arm caliper	A	14	12
West Tuna-8	Gippsland	Offshore	-38.189	148.37	153	BO	Image log	A	20	7
West Tuna-32	Gippsland	Offshore	-38.192	148.383	126	BO	Image log	C	4	3
West Tuna-37	Gippsland	Offshore	-38.194	148.373	148	BO	Image log	A	19	6
West Tuna-39	Gippsland	Offshore	-38.193	148.387	133	BO	Image log	A	11	10
West Tuna-44	Gippsland	Offshore	-38.209	148.382	125	BO	Image log	A	17	2
East Pilchard-1	Gippsland	Offshore	-38.198	148.562	132	BO	Image log	A	26	10
West Tuna-8	Gippsland	Offshore	-38.189	148.37	145	DITF	Image log	D	3	5

Table 10. Image logs from the Gippsland Basin interpreted as part of this study. BO refers to breakout. DITF refers to drilling-induced tensile fracture. Count relates to the number of BOs or DITFs interpreted in the well and SD is the standard deviation associated with the derived S_{Hmax} orientation.

Well	Basin	Location	Latitude	Longitude	S_{Hmax} Azimuth (ºN)	Type	Log	Quality	Count	SD
Koorkah–1	Bass	Offshore	-39.633	145.151	168	BO	four-arm caliper	B	21	20
Beardie–1	Gippsland	Offshore	-38.254	147.807	140	BO	Image log	D	3	9
Beardie–1	Gippsland	Offshore	-38.254	147.807	133	DITF	Image log	B	6	6
Longtom–1	Gippsland	Offshore	-38.098	148.316	104	BO	Image log	C	5	2
Longtom–1	Gippsland	Offshore	-38.098	148.316	139	DITF	Image log	D	1	0
Moonfish–1 st1	Gippsland	Offshore	-38.146	148.024	147	BO	Image log	B	8	11
Moonfish–1 st1	Gippsland	Offshore	-38.146	148.024	154	DITF	Image log	C	4	4
Blackback–3	Gippsland	Offshore	-38.56	148.518	168	BO	Image log	C	5	9

five of the 9 image logs interpreted in the Gippsland Basin. The maximum horizontal stress has been previously constrained using the occurrence of DITFs in the West Tuna area to ~39 MPa/km (Nelson and Hillis, 2005). This is slightly higher magnitude than was calculated in the Victorian Otway Basin and is associated with higher S_{hmin} magnitude. Discrete, horizontal fractures believed to be drilling-induced were observed at the azimuth of S_{Hmax} (in the tensile region) of the wellbore in West Tuna–8 and –39, Moonfish–1, Beardie–1, and Black Back–3 (Fig. 11). Nelson et al (2005) proposed that these transverse DITFs observed in West Tuna–8 and –39 could be used to help determine the magnitude of S_{Hmax} and determined it to be between 40.5 and 43.7 MPa/km (Nelson et al, 2005).

OVERVIEW OF THE PRESENT-DAY STATE-OF-STRESS IN SE AUSTRALIA

The most striking facet of the present-day state-of-stress of SE Australia is a province of ~1000 km extent from the SA Otway Basin to the Gippsland Basin, where S_{Hmax} is oriented northwest–southeast. As discussed below, this S_{Hmax} direction is almost orthogonal to the north-northeast direction of absolute plate motion and this has critical implications for the origins of stresses in SE Australia, and indeed throughout Australia. Looking in detail at regional S_{Hmax} orientations across SE Australia there is evidence for a clockwise rotation from 125° north in the SA Otway Basin to 137° north in the Victorian Otway Basin to 139°N in the

Table 11. Vertical stress profiles calculated in the Gippsland Basin.

Well	Basin	Location	Latitude	Longitude
Moray–1	Gippsland	Offshore	-38.8634	148.0557
Tuna-4	Gippsland	Offshore	-38.1892	148.3689
Kingfish–6	Gippsland	Offshore	-38.5944	148.2336
Tarwhine–1	Gippsland	Offshore	-38.4048	147.5281
Barracouta–4	Gippsland	Offshore	-38.2894	147.7011
Basker–1	Gippsland	Offshore	-38.3074	148.6981
Salmon–1	Gippsland	Offshore	-38.4206	147.9875
Baleen–1	Gippsland	Offshore	-38.0102	148.4357
Blackback–1	Gippsland	Offshore	-38.551	148.5617
Bream–5	Gippsland	Offshore	-38.5154	147.8662
Flounder–1	Gippsland	Offshore	-38.3144	148.4247
Hapuku–1	Gippsland	Offshore	-38.5556	148.549
Luderick–1	Gippsland	Offshore	-38.4391	147.7161
Halibut–1	Gippsland	Offshore	-38.3989	148.3164
Threadfin–1	Gippsland	Offshore	-38.5438	148.2562
Marlin–4	Gippsland	Offshore	-38.2401	148.2674
Snapper–4	Gippsland	Offshore	-38.2151	148.0039
Cobia–2	Gippsland	Offshore	-38.4588	148.3045

Gippsland Basin. We consider the regional S_{Hmax} orientation in the Bass Basin to be as yet undefined. Models for the present-day state-of-stress of Australia also show this clockwise rotation (Coblentz et al, 1998; Reynolds et al, 2003; Figs 2 and 3).

The magnitude of the minimum horizontal stress also varies from the SA Otway Basin where it is ~ 15.5 MPa/km to 18.5 MPa/km in the Victorian Otway Basin and 20 MPa/km in the Gippsland Basin. In the SA Otway Basin the interpreted stress regime is strike-slip changing to a strike-slip (towards border strike-slip/reverse) stress regime in the Victorian Otway Basin and in the Gippsland Basin the stress regime is on the border of strike-slip and reverse faulting.

The vertical stress does not vary significantly across SE Australia. Despite the large area studied, vertical stress is consistently ~20 MPa at 1 km depth and varies between ~63–69 MPa at 3 km depth.

The following sections compare the present-day state-of-stress determined from petroleum well data herein to focal mechanism and neotectonic data for the area. The origin of the regional northwest–southeast stress orientation and the variation in horizontal stress orientation and magnitude from west to east across SE Australia are also discussed.

COMPARISON WITH STRESS INDICATORS FROM EARTHQUAKES

Petroleum (well) data reveal the present-day state-of-stress in the upper few kilometres of the crust (to 3.5 km in the case of this study). Focal mechanism analyses of earthquakes also reveal variation on the orientations and relative magnitudes of present-day stress (Denham et al, 1979). Focal mechanism solutions reveal stresses in the deeper seismogenic zone. In the case of the intra-continental earthquakes of SE Australia, focal depths are typically between 5–20 km (Denham et al, 1979; Allen et al, 2004). It is interesting to compare present-day stresses inferred from the two sources of data in order to gain a more complete picture of the present-day state-of-stress and

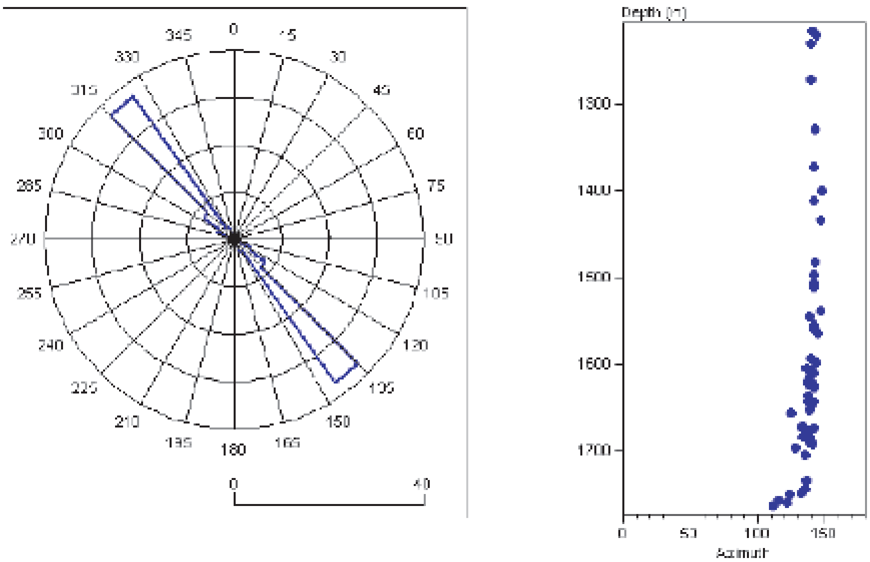


Figure 7. Rose plot of S_{Hmax} orientation (left) and depth plot of S_{Hmax} orientation (right) based on the interpretation of 53 A–C quality DITFs interpreted in the Minerva–1 and Minerva–2a wells in the Victorian Otway Basin.

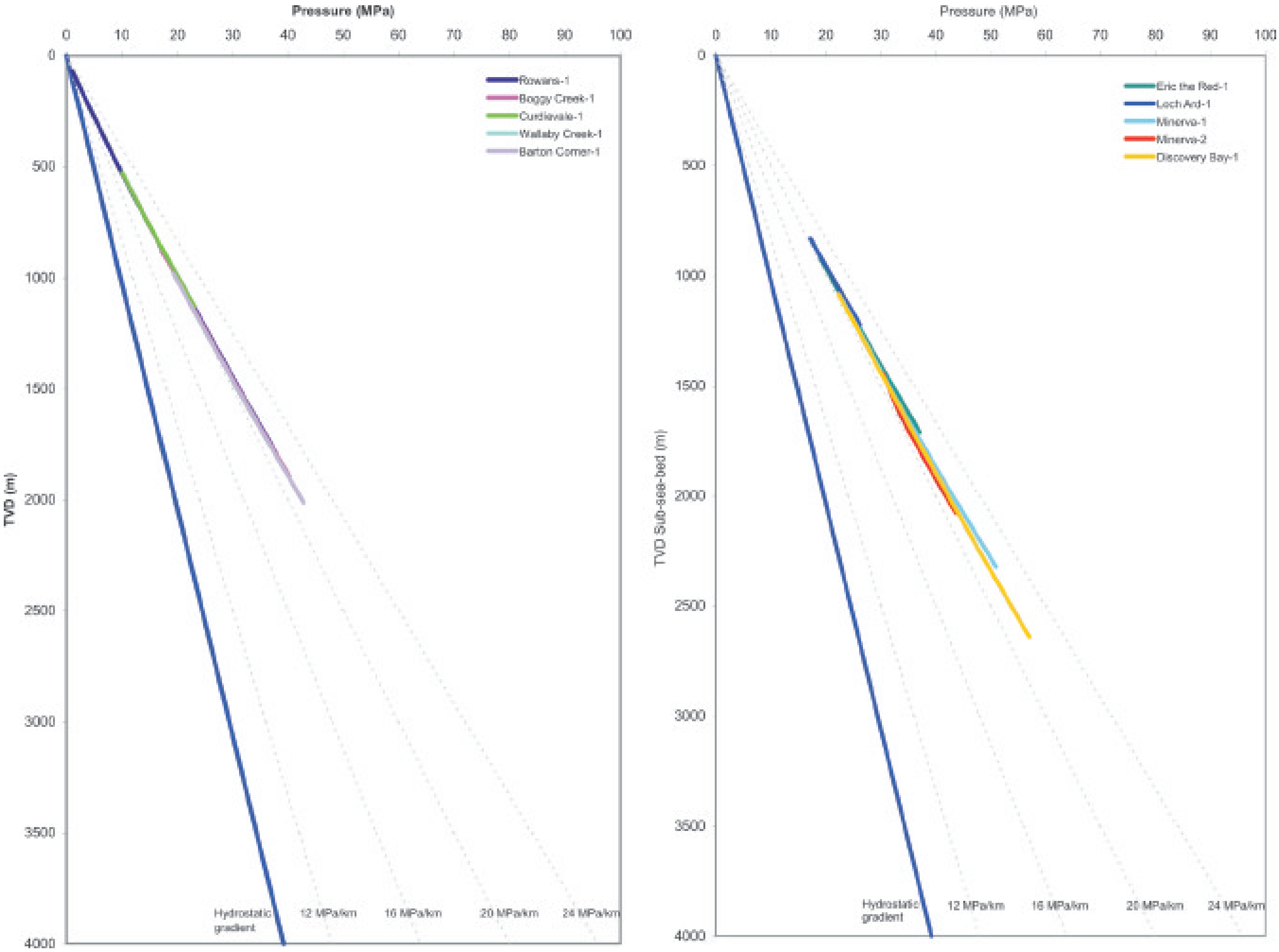


Figure 8. Vertical stress profiles from the onshore Victorian Otway Basin (left) and the offshore Victorian Otway Basin (right).

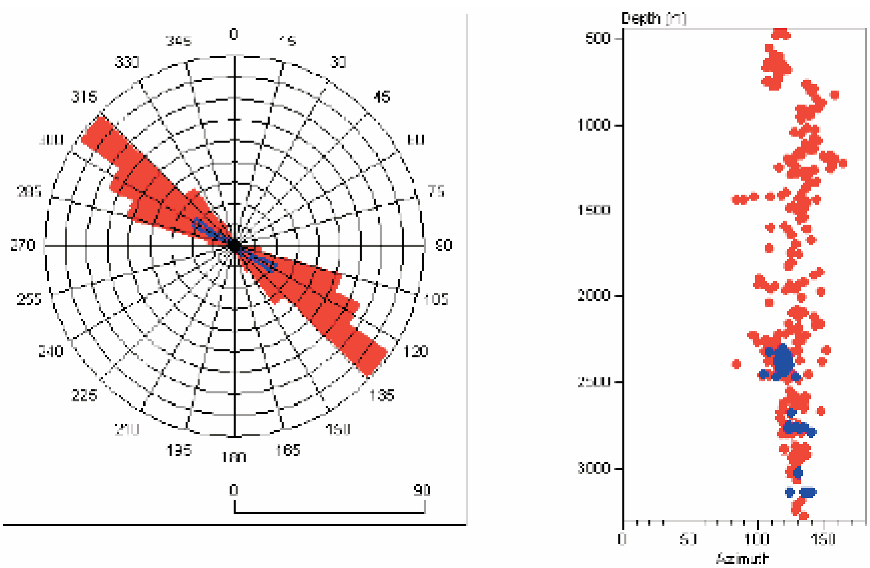


Figure 9. Rose plot of S_{Hmax} orientation (left) and depth plot of S_{Hmax} orientation (right) based on the interpretation of 169 A–C quality breakouts (red data) and 10 A–C quality DITFs (blue data) interpreted in the Gippsland Basin.

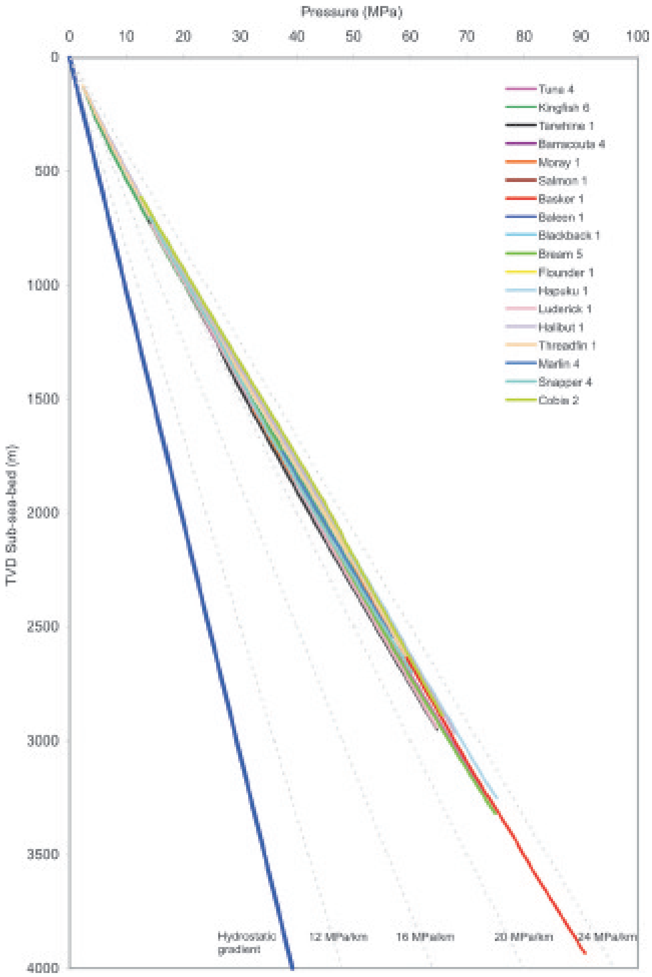


Figure 10. Vertical stress profiles from the offshore Gippsland Basin.

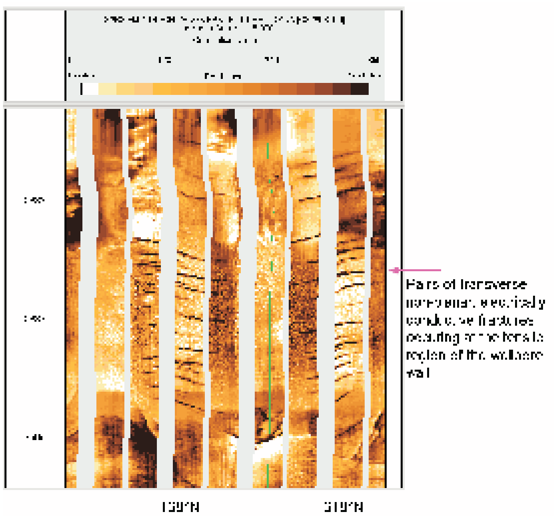


Figure 11. Transverse DITFs interpreted on an image log from the West Tuna–39 well. The fractures are electrically conductive, transverse (at the azimuth of S_{Hmax}), restricted to the tensile region of the wellbore and non-planar.

to investigate whether stresses in the sedimentary basins are the same as those in the underlying basement.

SE Australia is one of the most seismically active parts of the Australian continent (Fig. 12). Concentrations in seismic activity occur in the Mount Lofty Ranges/Flinders Ranges/Gawler Craton region of South Australia and in the south-central Victorian Snowy Mountains/Eastern Highlands (Fig. 12). The Otway Basin is relatively aseismic and no focal mechanism solutions have been determined in the area. Dominantly strike-slip and reverse focal mechanisms have been recorded in the Flinders Ranges. These suggest an S_{Hmax} orientation of ~082° north (Greenhalgh et al, 1994; Clark and Leonard, 2003). The strike-slip earthquake focal mechanisms are consistent with the strike-slip stress regime determined herein for the adjacent SA Otway Basin. The east–west S_{Hmax} orientation in the Flinders Ranges is also consistent with anticlockwise stress rotation from west to east across SE Australia.

Analyses of petroleum well data herein suggest a strike-slip to borderline strike-slip/reverse stress regime in the Victorian Otway Basin. This is consistent with the strike-slip focal mechanism determined to the north at Nhill in Victoria (located just east of the Victorian border; Table 13; Fig. 3).

In the Snowy Mountains (Eastern Highlands) reverse focal mechanisms are associated with a northwest–southeast (~135° north) azimuth for S_{Hmax} (Gibson et al, 1981; Clark and Leonard, 2003). Analysis of petroleum well data herein suggests a borderline strike-slip/reverse stress regime with a similarly oriented S_{Hmax} in the Gippsland Basin. However, leak-off tests are not able to determine the magnitude of the minimum horizontal stress if it is greater than S_v and hence are unable to distinguish between a borderline strike-slip/reverse stress regime and a truly reverse stress regime. It is quite possible that the stress regime in the Gippsland Basin is one of reverse faulting as the focal mechanism solutions suggest.

In summary, we believe there is good agreement between stresses inferred from focal mechanism solutions and petroleum well data in SE Australia and that S_{Hmax} rotates anticlockwise from about east–west in the Flinders ranges through ~125° north in the SA Otway Basin to ~140° north in the Gippsland Basin. Focal mechanisms also suggest an increase in stress magnitude from west to east, with dominantly strike-slip focal mechanisms in the Flinders Ranges, and dominantly reverse focal mechanisms in the Eastern Highlands that are also consistent with the stress tensors derived herein from petroleum well data. We see no evidence of detachment of stress between the sedimentary basins (petroleum data) and the underlying basement (focal mechanism solution data) in SE Australia.

COMPARISON WITH THE NEOTECTONIC RECORD

The late-Neogene to recent geological record of SE Australia indicates significant periods of faulting and deformation (Dickinson et al, 2002; Sandiford et al, 2004). Although there is no Recent faulting evident in the SA Otway Basin,

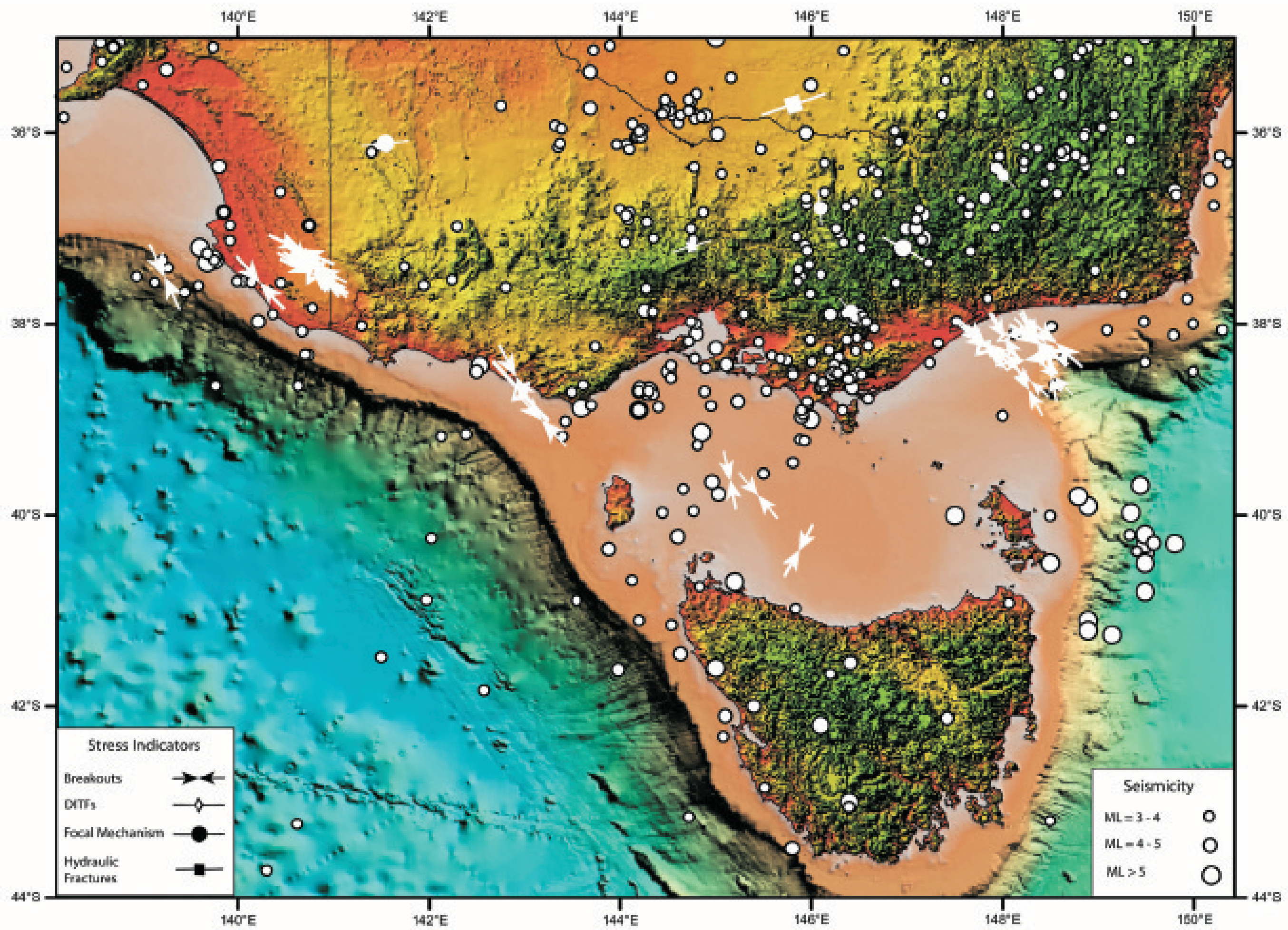


Figure 12. Location of earthquakes of magnitude three or greater that have occurred in SE Australia since 1960. The S_{Hmax} orientations derived from data compiled herein are also shown.

the Flinders and Mt Lofty Ranges in South Australia are bounded by north–south to northeast–southwest trending fault scarps (including the Willunga, Para, Eden-Burnside, Ochre Cove, Willunga and Milendella faults). Sandiford et al (2004) found that reverse motion on these faults is Recent with Proterozoic to Cambrian age basement thrust over Quaternary conglomerates. Recent reverse motion on these faults is in contrast to the dominantly strike-slip focal mechanism solutions derived in the Flinders Ranges and the strike-slip stress tensor derived from petroleum well data in the adjacent SA Otway Basin. The reason for this discrepancy is unclear. It is possible that the stress state relaxes after periods of faulting prior to building up again due to the far-field tectonic stresses to promote slip again. Alternatively there may be some partitioning across the ranges such that the range bounding faults tend to be reverse, while those inside the ranges tend to be strike-slip (Sandiford, 2003a; Célérier et al, 2005; Quigley et al, 2006).

The Otway Ranges in southwest Victoria also witness Quaternary reverse tectonism with evidence of ~200 m of uplift since the early to mid-Pliocene (Dickinson et al, 2002; Sandiford et al, 2004). The orientation of faults and anticlines is consistent with an S_{Hmax} orientation of ~150° north (Sandiford et al, 2004). Figure 13 shows that the orientation of faults with evidence of neotectonic activity are broadly consistent with the stress orientations derived herein. Similarly, the Minerva anticline has also been shown to have experienced pulses of compression from the Miocene to Recent (Schneider et al, 2004). As in the Flinders Ranges, evidence for reverse faulting in the neotectonic record close to the Victorian Otway Basin is in contrast to the strike-slip focal mechanism from the Nhill area and the present-day stress tensor determined herein.

The Strezlecki ranges in south Gippsland also are bounded by northeast–southwest trending structures (Fig. 13) which also show evidence of Recent movement, although unlike the Flinders Ranges, the absence of exposures of active faults in this region has precluded unequivocal determination of reverse slip (Sandiford, 2003b). The neotectonic record and earthquake focal mechanism solutions are consistent in suggesting a reverse stress regime in the Gippsland Basin and a northwest–southeast S_{Hmax} orientation. The present-day stress tensor determined from

Table 12. Leak-off pressures (LOTs) and reported leak-off pressures (RLOTs) from wells in the Gippsland Basin.

Well	Basin	Location	Latitude	Longitude	Depth (m)	Pressure (MPa)	Test type
Admiral–1	Gippsland	Offshore	38.15	148.65	1078.00	27.50	RLOT
Amberjack–1	Gippsland	Offshore	38.49	147.32	3041.00	53.69	RLOT
Archer–1	Gippsland	Offshore	38.77	148.31	979.00	16.37	LOT
Athene–1	Gippsland	Offshore	38.60	148.46	507.00	6.78	RLOT
Athene–1	Gippsland	Offshore	38.60	148.46	1170.00	20.32	RLOT
Baleen–1	Gippsland	Offshore	38.01	148.44	200.05	3.55	RLOT
Baleen–1	Gippsland	Offshore	38.01	148.44	556.55	10.98	RLOT
Basker–1	Gippsland	Offshore	38.31	148.70	1225.00	20.99	RLOT
Basker South–1	Gippsland	Offshore	38.32	148.69	1075.00	17.44	RLOT
Blackback–1	Gippsland	Offshore	38.55	148.56	473.00	7.56	RLOT
Blenny–1	Gippsland	Offshore	38.47	147.41	675.00	10.43	RLOT
Devilfish–1	Gippsland	Offshore	38.80	147.92	784.50	17.12	LOT
Devilfish–1	Gippsland	Offshore	38.80	147.92	1060.20	20.96	RLOT
Edina–1	Gippsland	Offshore	38.61	147.88	802.00	16.91	RLOT
Grunter–1	Gippsland	Offshore	38.27	148.52	1165.60	19.19	RLOT
Gudgeon–1	Gippsland	Offshore	38.52	148.47	834.00	15.22	RLOT
Gummy–1	Gippsland	Offshore	38.30	148.74	3528.00	80.92	RLOT
Gummy–1	Gippsland	Offshore	38.30	148.74	528.60	7.21	RLOT
Halibut–1	Gippsland	Offshore	38.40	148.33	2972.00	51.00	RLOT
Helios–1	Gippsland	Offshore	38.70	148.28	318.00	3.96	RLOT
Helios–1	Gippsland	Offshore	38.70	148.28	1155.60	20.48	RLOT
Kipper–1	Gippsland	Offshore	38.18	148.60	809.00	16.38	LOT
Leatherjacket–1	Gippsland	Offshore	38.09	148.78	605.00	11.17	RLOT
Loy Yang–1	Gippsland	Offshore	38.25	146.56	254.10	5.19	RLOT
Luderick–1	Gippsland	Offshore	38.44	147.72	771.00	15.63	RLOT
Manta–1	Gippsland	Offshore	38.27	148.72	803.20	13.22	RLOT
Manta–1	Gippsland	Offshore	38.27	148.72	740.00	12.69	RLOT
Patricia–1	Gippsland	Offshore	38.03	148.45	917.00	17.74	RLOT
Perch–4	Gippsland	Offshore	38.57	147.32	779.00	15.22	RLOT
Seahorse–1	Gippsland	Offshore	38.20	147.67	1241.00	26.38	RLOT
Snapper–4	Gippsland	Offshore	38.22	148.00	1480.00	29.26	RLOT
Teraglin–1	Gippsland	Offshore	38.38	148.34	3198.00	63.13	RLOT
Terakihi–1	Gippsland	Offshore	38.51	148.55	2413.00	48.00	RLOT
Tommyruff–1	Gippsland	Offshore	38.61	147.14	773.00	17.16	RLOT
Trumpeter–1	Gippsland	Offshore	38.41	148.35	1103.00	21.12	RLOT
Tuna–4	Gippsland	Offshore	38.19	148.37	762.00	12.97	LOT
Veilfin–1	Gippsland	Offshore	38.42	148.00	794.00	15.50	RLOT
Whaleshark–-1	Gippsland	Offshore	38.40	148.89	2133.00	43.75	LOT
Wrixondale–1	Gippsland	Offshore	38.00	147.50	275.80	6.19	RLOT

Table 13. Earthquake focal mechanisms determined close to the Victorian Otway Basin and the Gippsland Basin. SS and TF refer to strike and thrust fault stress regimes respectively.

Location	State	Latitude	Longitude	Stress regime	S_{Hmax} orientation (°N)	Quality
Nhill	Victoria	-36.107	141.539	SS	84	B
Wonnangatta	Victoria	-37.205	146.956	TF	119	B
Corryong	Victoria	-36.441	148.005	SS	137	C
Tatong	Victoria	-36.781	146.094	TF	174	C
Thomson Reservoir	Victoria	-37.863	146.422	TF	141	C
Dalton-Gunning	NSW	-35.03	149.02	SS	91	C

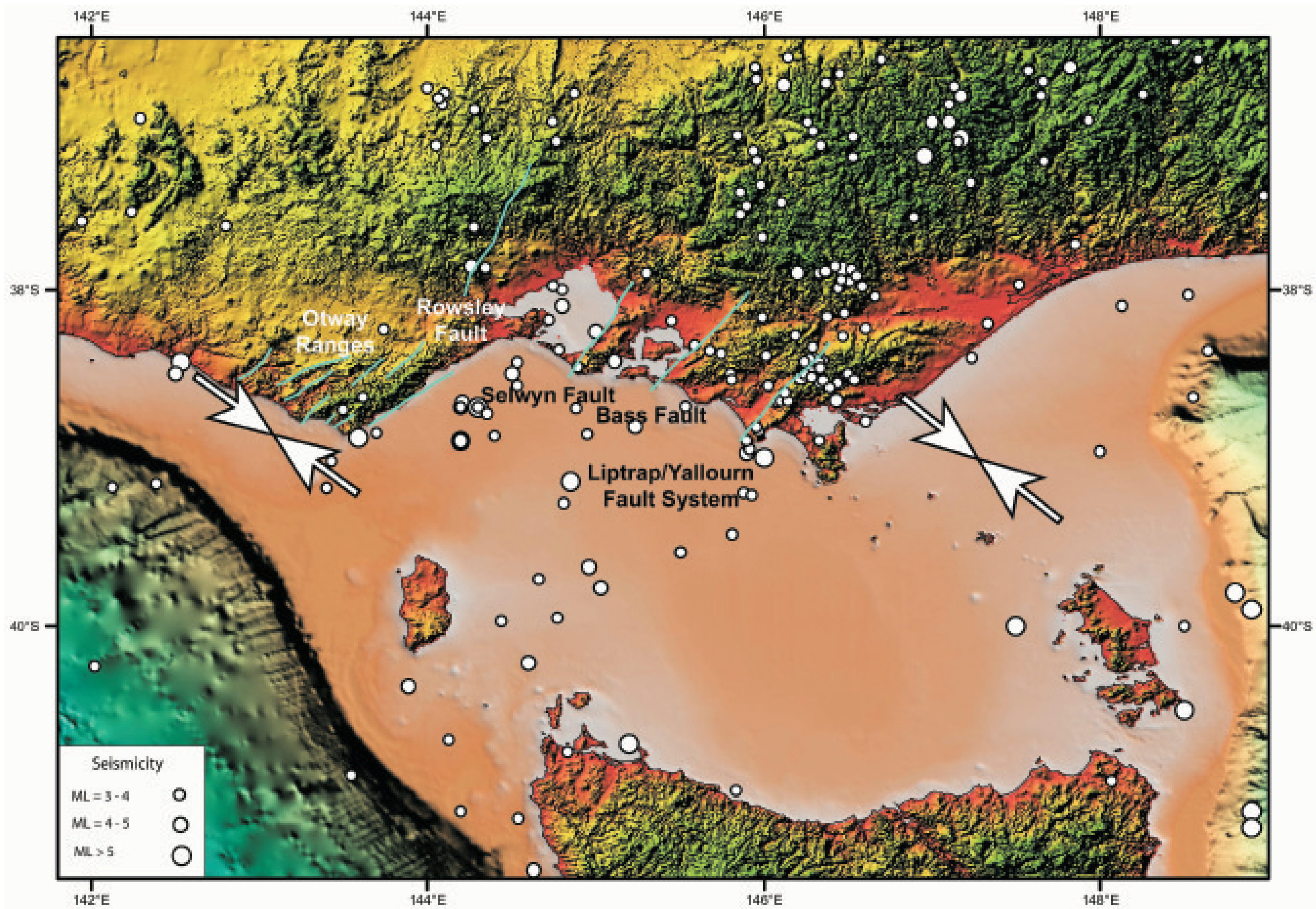
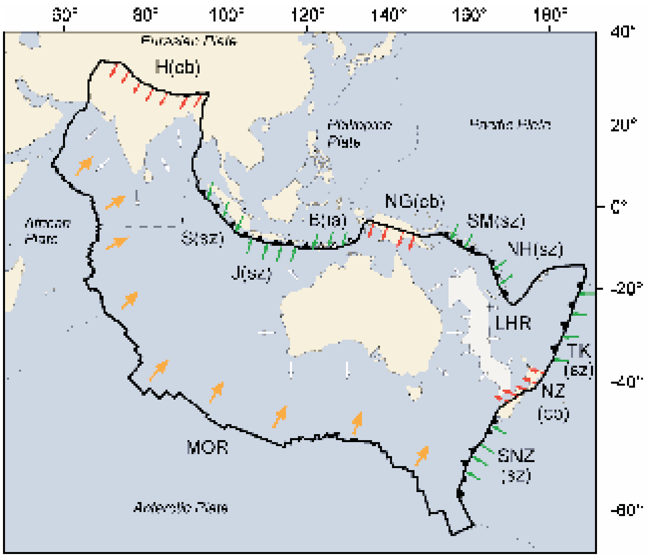


Figure 13. Comparison between the orientation of faults (blue) known to have reactivated due to compression during the Neogene (from Sandiford et al (2003) and Dickinson et al (2002)) the average S_{Hmax} orientations determined in the Victorian Otway and Gippsland Basin.



petroleum data suggests a borderline strike-slip/reverse regime and a northwest–southeast S_{Hmax} orientation.

IMPLICATIONS FOR THE ORIGIN OF REGIONAL STRESSES IN SE AUSTRALIA

In most plates the maximum horizontal stress orientation parallels the direction of absolute plate motion and it is thus inferred that the forces that drive and resist plate motion are responsible for the present-day stress field (Zoback, 1992). In SE Australia we have defined a province of some 1,000 km extent where northwest–southeast oriented

Figure 14 (left). Indo-Australian plate with the boundary forces used in the modelling of Reynolds et al, (2003). Orange arrows indicate mid-ocean ridge force, red and green arrows indicate plate-boundary forces. H, Himalaya; S, Sumatra Trench; B, Banda arc; NG, New Guniea; SM, Solomon Trench; NH, New Hebrides; TK, Tonga-Kermadec Trench; NZ, New Zealand; SNZ, south of New Zealand; MOR, mid ocean ridge; cb, collisional boundary; sz, subduction zone; ia, island arc.

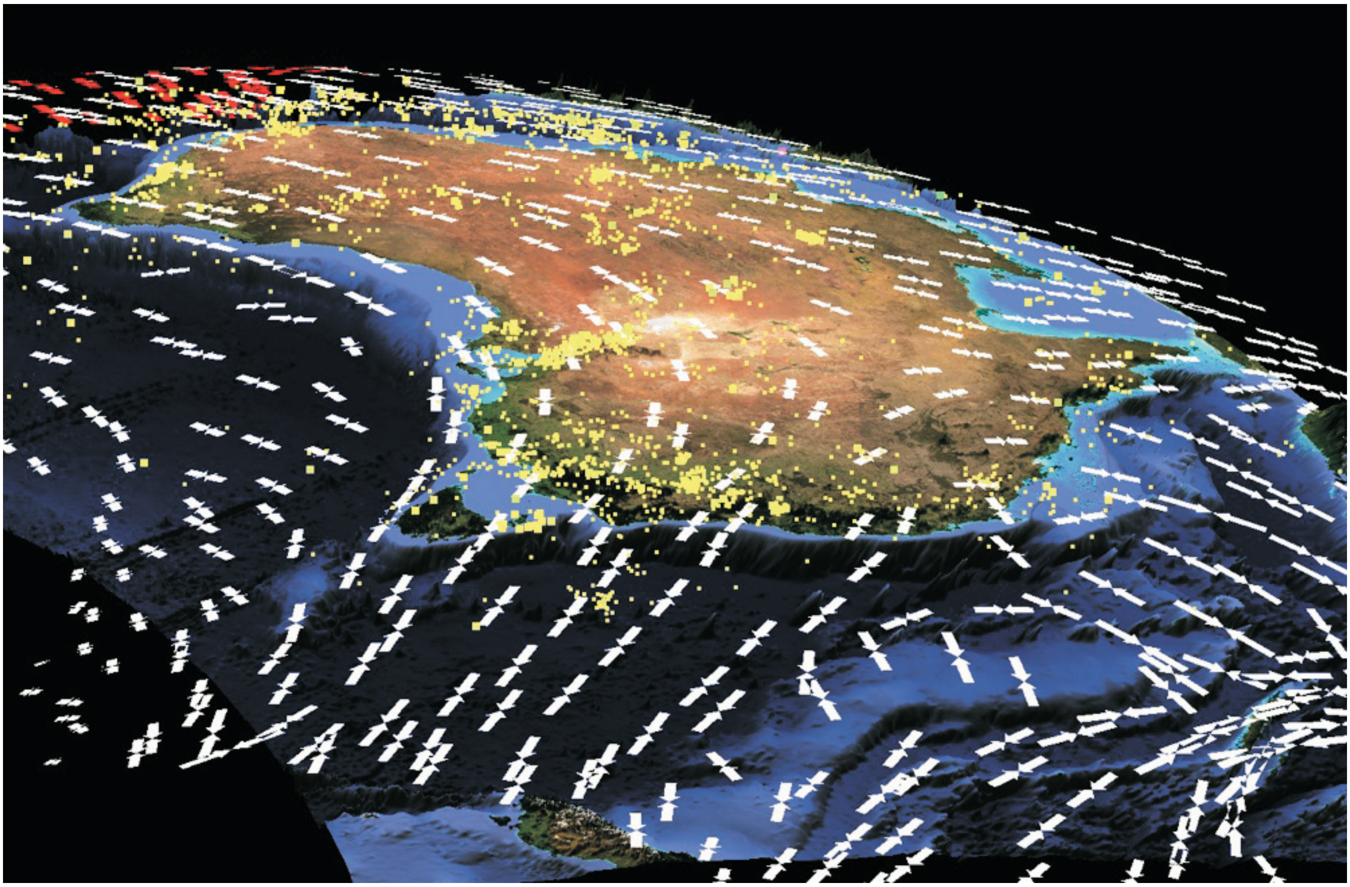


Figure 15. Maximum horizontal stress orientation trajectories showing the stress rotations across the Australian continent due to plate boundary forces (from Mike Sandiford's website).

S_{Hmax} is almost orthogonal to the northnortheast motion of the Australian Continent. Nonetheless, plate-scale modelling has shown that the present-day stress orientation in Australia, including the northwest–southeast S_{Hmax} orientation of SE Australia, are consistent with a plate boundary force control on the intra-plate stress field—provided that the complex nature of the northeastern convergent plate boundaries of the Indo-Australian plate are considered (Coblentz and Richardson, 1995; Coblentz et al, 1998; Reynolds et al, 2002).

Analysis of breakouts and DITFs on image logs from SE Australia indicate that S_{Hmax} rotates from ~125° north in the South Australian sector of the Otway Basin through ~137° north in the Victorian Otway Basin to ~140° north in the Gippsland Basin. We have also noted an increase in horizontal stress magnitude from west to east across SE Australia. We believe that this rotation is part of a broader rotation of S_{Hmax} from east–west in southwest and south central Australia to nothwest–southeast in SE Australia. The modelling of Coblentz et al. (1998) and Reynolds et al.(2002, 2003) has shown that compressional forces along the New Zealand and south of New Zealand plate boundary segments can account for the east–west to northwest–southeast maximum horizontal stress directions from the SA Otway Basin to the Gippsland Basin (Figs. 14 and 15).

Whilst the rotation in S_{Hmax} orientation can be explained in terms of plate boundary forces, and, in particular, the plate boundary forces at New Zealand, the change in minimum horizontal stress magnitude from ~ 15.5° MPa/km to ~20 MPa/km in the Gippsland Basin is not as easy to model. Possibly the simplest explanation is that the horizontal stress magnitude (and differential stress magnitude) is dependent on proximity to the compressional part of the plate boundary in New Zealand. It is therefore a possibility that the higher horizontal stress magnitudes in the Gippsland Basin are due largely to its proximity to the compressional boundary at New Zealand. It is worth noting that there is evidence of pulses of compression and inversion from the Eocene to mid-Miocene in both the Gippsland and Bass Basins (Power et al, 2003; Cummings et al, 2004). However, this inversion occurred prior to the plate boundary at New Zealand becoming dominantly compressional, and, as such, the inversion events must be due to a different tectonic driver than is active today.

CONCLUSIONS

Analysis of petroleum well data from the Otway and Gippsland Basins has shown that S_{Hmax} is oriented broadly northwest–southeast across SE Australia. This orientation is consistent with S_{Hmax} orientations derived from focal mechanism solutions, neotectonic structures from SE Australia and with previous modelling of plate-boundary forces by other authors. The consistency between orientations derived from the deep (basement) focal mechanism solutions (~5–20 km) and the shallow petroleum well data (0–3.5 km) suggest a dominant tectonic (far-field/plate-boundary) influence on the state-of-stress in SE Australia.

The present-day state-of-stress measured from petroleum well data was observed to increase in magnitude from dominantly strike-slip ($S_{Hmax}>S_v>S_{hmin}$) in the SA Otway Basin to strike-slip trending towards reverse in the Victorian Otway Basin to borderline strike-slip/reverse ($S_{Hmax}>S_v\sim S_{hmin}$) in the Gippsland Basin. As with the S_{Hmax} orientations described above, these stress-states are broadly consistent with focal mechanism solutions which show a dominantly strike-slip stress-state in the Flinders Ranges (west of the Otway Basin) and a reverse stress-state in the Eastern Highlands (of Victoria and NSW). It is not possible to use petroleum well data to measure a purely reverse ($S_{Hmax}>S_{hmin}>S_v$) stress regime. It is possible that a purely reverse stress regime does exist in the shallow (<3.5 km) section of the Gippsland Basin that is consistent with the focal mechanism solutions.

Neotectonic structures in SE Australia suggest a dominantly reverse state-of-stress in SE Australia. This is in contrast to the strike-slip stress-state and strike-slip focal mechanism solutions measured in the Otway Basin and Flinders Ranges. One possible explanation for this discrepancy is that the stress state relaxes after periods of faulting prior to building up again under the influence of the far-field tectonic stresses to promote slip again. The Otway Basin (and Flinders Ranges) may be in a relaxed state at the present time.

The S_{Hmax} orientation was observed to rotate ~15° clockwise from the SA Otway Basin to the Gippsland Basin. The magnitude of S_{hmin} was also observed to increase from ~15.5 MPa/km in the SA Otway Basin to 18.5 MPa/km in the Victorian Otway Basin to ~20 MPa/km in the Gippsland Basin. The clockwise rotation and increase in horizontal stress magnitude from west to east across SE Australia may be due to proximity of the compressional New Zealand sector of the plate boundary.

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APPEA

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