Maximum horizontal stress orientations in the Cooper Basin, Australia: implications for plate-scale tectonics and local stress sources

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SUMMARY
Borehole breakouts and drilling-induced tensile fractures (DITFs) were interpreted in 61 wells in the Cooper Basin indicating an average maximum horizontal stress orientation of 101°N. A total of 890 borehole breakouts and 608 DITFs were interpreted in the Cooper Basin. The approximately east–west maximum horizontal stress orientation is consistent over much of the basin, except in the Patchawarra Trough where maximum horizontal stress rotates to a northwest–southeast orientation. This rotation in maximum horizontal stress orientation is consistent with in situ stress data to the northwest of the Cooper Basin. The stress field in the Cooper Basin appears to mark the apex of a major horseshoe-shaped rotation in maximum horizontal stress direction across central eastern Australia. Finite element modelling of the in situ stress field of the Indo–Australian Plate (IAP) using a range of plate-scale tectonic forces is able to match the regional maximum horizontal stress orientation over most of Australia reasonably well, including the mean east–west maximum horizontal stress orientation in the Cooper Basin. However, plate boundary–scale modelling does not adequately match the horseshoe-shaped stress rotation across central eastern Australia. The average east–west maximum horizontal stress orientation in the Cooper Basin indicates that stresses from tensional forces acting along the Tonga–Kermadec subduction zone are not transmitted into the interior of the Australian plate. The majority of the tensional forces associated with the Tonga–Kermadec subduction zone are most likely accommodated along the numerous spreading centres within the Lau–Havre backarc basin. A number of more localized stress anomalies have also been identified. These cannot be explained by plate-scale tectonic forces and are possibly a result of geological structure and/or density contrasts locally perturbing the stress field.

Key words: Cooper Basin, plate tectonics, stress orientation.

1 INTRODUCTION
In most continental areas, the first-order maximum horizontal stress ($S_{\text{Hmax}}$) orientation is consistent and broadly matches the direction of absolute plate velocity (Zoback et al. 1989; Richardson 1992; Gölke & Coblentz 1996). Thus, the first-order intraplate stress field appears to be controlled by plate driving forces such as ridge push (Zoback et al. 1989; Richardson 1992). In contrast, the Australian intraplate stress field is highly variable and does not parallel the north-northeast direction of absolute plate velocity for the Indo–Australian Plate (IAP). Consequently, on initial inspection, plate driving forces do not appear to control the first-order intraplate stress field in continental Australia. However, a number of studies have shown that plate driving forces do indeed play a critical role in controlling the Australian intraplate stress field if the heterogeneous convergent northeastern boundary of the IAP is recognized (Cloetingh & Wortel 1986; Coblentz et al. 1995, 1998). Thus, the complex nature of the Australian stress field provides an ideal location to investigate the interaction between the intraplate stress field and plate boundary forces. In this study, we present a large number of high-quality in situ stress data for the Cooper Basin, which adds significantly to our understanding of the nature as well as the underlying controls of the stress field in continental Australia.

The Cooper Basin is a northeast–southwest trending intracratonic basin located in central Australia (Fig. 1). The basin is located a
significant distance from the nearest plate boundary and hence provides an ideal location to test the influence of plate boundary forces acting on the IAP. When combined with stress information from surrounding areas, the Cooper Basin plays a critical role in constraining the modelled stress field in central Australia. Furthermore, the $S_{Hmax}$ orientation in the Cooper Basin is approximately perpendicular to the north-northeast direction of absolute plate velocity for the IAP.

The Cooper Basin is the largest onshore oil and gas province in Australia. Extensive drilling has occurred in the Cooper Basin since the first natural gas discovery in 1963. As a result, a substantial database of high-quality image log data exists for the Cooper Basin. Data presented in this study comes from both the South Australia and Queensland sectors of the basin and comprises a total of 42 image logs providing over 19 km of well bore image. A number of older dipmeter logs have also been included in the analysis.

The in situ stress data in the Cooper Basin is important to our understanding of the Australian stress field, as limited in situ stress data exist for central Australia. The stress data that is available indicates a range of $S_{Hmax}$ orientations from north–south in the Amadeus and Bowen basins (Fig. 2), to a highly scattered east–west orientation in the Flinders Ranges and also a variable $S_{Hmax}$ orientation in the Sydney Basin (Hillis et al. 1999; Hillis & Reynolds 2000; Fig. 2). Thus in situ stress data for the Cooper Basin is critical to understanding the Australian stress field. Previously published stress data has indicated an average east–west $S_{Hmax}$ orientation in the Cooper Basin (Hillis & Reynolds 2000). However, this was only based on 14 stress measurements and, hence, did not reveal many of the stress field features uncovered by this study.

### 2 TECTONIC AND GEOLOGICAL SETTING

The Cooper Basin is a Late Carboniferous to Middle Triassic, non-marine sedimentary basin located in central Australia (Hill & Gravestock 1995). The focus of this study was on the South Australia and adjacent Queensland sectors of the basin. The South Australia sector of the basin contains the greatest thickness of productive Permian strata and hence the largest amount of well data (Gravestock & Jensen-Schmidt 1998). Consequently the majority of the stress data is located in the South Australia sector of the basin. A major unconformity occurs at the top of the Cooper Basin separating it from the overlying Eromanga Basin of Jurassic to Cretaceous age (Apak et al. 1997). Depth to the unconformity varies from 970 to 2800 m (Laws & Gravestock 1998). The Cooper Basin reaches a maximum depth of approximately 4400 m in its deepest trough (Laws & Gravestock 1998).
Maximum horizontal stress orientations

Figure 2. The Australian stress field. Maximum horizontal stress orientations are plotted for all the A–C quality data. Vector length represents the data quality. Solid, open and semi-solid stress indicator symbols represent compressional (TF), extensional (NF) and strike-slip (SS) deformation style, respectively. Grey shading indicates the horseshoe-shaped $S_{\text{Hmax}}$ rotation across the central eastern part of the Australian continent referred to in the text. Focal mechanism = earthquake focal mechanism; breakout = borehole breakout; overcoring = overcoring measurements; hydro. fractures = hydraulic fracture measurements; geol. indicators = geological indicators; DI tensile fractures = drilling-induced tensile fractures.

In Australian terminology, overlying, successor basins are generally given different names. The Eromanga Basin is a successor basin overlying, but more widespread than, the Cooper Basin. The majority of the stress data included herein come from the Late Carboniferous to Middle Triassic Cooper Basin. However, some stress data are from the overlying Jurassic to Cretaceous Eromanga Basin, but only within the same geographic area of subcrop as the Cooper Basin. Hence, for the sake of simplicity we refer to this study as covering the Cooper Basin.

The South Australia sector of the Cooper Basin comprises a series of northeast to southwest trending ridges and troughs. The major depocentres include the Patchawarra Trough, the Nappamerri Trough and the Tennapara Trough, which are separated by two major intrabasin highs, the Gidgealpa–Merrimelia–Innaminka (GMI) Ridge and the Muteree–Nappacoongee Ridge (Fig. 1). The Nappamerri Trough extends into the Queensland sector of the basin, which also contains a number of less prominent structural features. The Arrabury–Karmona trend divides the basin into southern and northern parts, with the southern part containing most of the Permian depocentres and the northern part containing most of the Triassic depocentres (Gravestock & Jensen-Schmidt 1998). The majority of the well data used in this study is located on the intrabasin highs surrounding the major troughs. However, a few of the wells analysed are located in the Patchawarra and Nappamerri troughs.

3 BORREHOLE BREAKOUT AND DRILLING-INDUCED TENSILE FRACTURE ANALYSIS

Borehole breakouts and drilling-induced tensile fractures (DITFs) have been interpreted from both image and dipmeter log data to determine the in situ stress field for the Cooper Basin. Borehole breakouts form when the circumferential stress acting around a well bore exceeds the compressive strength of the rock (Bell & Gough 1979; Zoback et al. 1985; Fig. 3). When this arises in a vertical well, conjugate shear fractures form at the well bore wall centred on the minimum horizontal stress ($S_{\text{hmin}}$) direction, causing the rock to spall off (Gough & Bell 1982). As a consequence, the well bore becomes enlarged in the $S_{\text{hmin}}$ direction (Fig. 3).

Borehole breakouts can be interpreted using either dipmeter or imaging tools. The high-resolution dipmeter tool (HDT) was commonly used in older wells and has now been largely replaced by imaging tools. A number of wells with dipmeter logs have been included in this study, however the majority of the analysis in this study has been conducted on wells with image log data from Schlumberger’s Formation Microscanner (FMS) tool. The FMS tool consists of four pads with 16 buttons on each pad that measure microresistivity variations of the rock surrounding the borehole. Schlumberger’s newer image tool, the Formation Microimager (FMI), has been run in a small number of wells on the Queensland sector of the basin.
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Figure 3. Circumferential stress around a vertical well bore with respect to the $S_{\text{Hmax}}$ orientation. Breakout formation occurs where the circumferential stress exceeds the compressive rock strength. Drilling-induced tensile fracture (DITF) formation occurs at 90° to the breakouts where the circumferential stress is less than the tensile rock strength.

The FMI tool consists of four pads and four flaps each with 24 buttons providing significantly increased well bore coverage. Borehole breakouts on image logs are generally poorly resolved (poor padwall contact), blobby zones of low resistivity where drilling mud has invaded breakout-related fractures (Fig. 4).

DITFs form in the orientation of $S_{\text{Hmax}}$ when the circumferential stress around the well bore is less than the tensile strength of the rock (Brudy & Zoback 1999; Fig. 3). Their formation is analogous to fracture initiation during a hydraulic fracture test and is the result of the natural stress state being perturbed by drilling. However, DITFs do not propagate into the well bore wall unless the well bore fluid pressure exceeds the minimum principal stress (Barton et al. 1998). Hence no lost mud is recorded. DITFs can form under a wide range of stress conditions and do not necessarily require significant well bore fluid pressures (Peska & Zoback 1995). The DITFs are dark in colour (high conductivity) as they are filled by drilling mud. They generally have well-defined edges (Fig. 4). In contrast, cemented natural fractures tend to be resistive. DITFs can only be recognized on image logs (Fig. 4).

A magnetic declination correction of between 7° and 8° east had previously been applied to all logs prior to interpretation. Each well containing borehole breakouts was ranked using the World Stress Map (WSM) scheme (Zoback 1992). The wells containing DITFs were ranked using the same criteria set out in the WSM scheme for borehole breakouts, because no formal criteria for ranking DITFs exists.

4 STRESS ORIENTATIONS IN THE COOPER BASIN AND SURROUNDING AREAS

A total of 890 borehole breakouts and 608 DITFs have been interpreted from 61 wells in the Cooper Basin (Tables 1 and 2). Borehole breakouts were interpreted in 57 wells while 27 wells were interpreted to contain DITFs. Only wells ranked A to C quality on the WSM ranking scheme were considered to have a statistically significant average $S_{\text{Hmax}}$ orientation. Thus, D-quality wells were not included in the statistical analysis and were not plotted on Fig. 5. Nevertheless, D-quality wells are listed in Tables 1 and 2 in order to provide a record of all wells analysed as part of this study. The mean of the mean $S_{\text{Hmax}}$ orientations in the 47 wells with A–C quality borehole breakouts is 100°N (Table 3). The mean of the mean $S_{\text{Hmax}}$ orientations in the 17 wells with A–C quality DITFs is 104°N (Table 3). The mean $S_{\text{Hmax}}$ orientation from all wells with A–C quality borehole breakouts and DITFs is 101°N (Table 3). Overall the variation of the average $S_{\text{Hmax}}$ orientation inferred from different stress indicator types and qualities is very small.

On average, the stress data for the Cooper Basin indicate an approximately east–west $S_{\text{Hmax}}$ orientation. However, a number of geographic/geological domains have their own distinct stress trends. Stress data from four wells in the Patchawarra Trough indicate a southeast–northwest $S_{\text{Hmax}}$ orientation (Fig. 5). Wells northeast of Gigealpa-47 on the GMI ridge exhibit a west-northwest to east-southeast $S_{\text{Hmax}}$ orientation. In the Nappamerri Trough the stress data indicate an east–west $S_{\text{Hmax}}$ orientation. This systematic rotation is shown more clearly on the stress trajectory map of the region (Fig. 6). The stress trajectory map indicates the averaged $S_{\text{Hmax}}$ orientation at a given location. The stress trajectories have been calculated in order to highlight the regional trend and thus smooth any local variations such as that seen in Cowan-3. Consequently, all A to D quality stress data were included in the stress trajectory calculations and were weighted accordingly (i.e. A-quality = 4, B-quality = 3, C-quality = 2, D-quality = 1). A detailed description of the stress trajectory technique can be found in Hansen & Mount (1990). The southeast–northwest $S_{\text{Hmax}}$ orientation in the Patchawarra Trough is also observed in Malgoona-3 located on the western edge of the basin. However, the stress trajectories do not match this rotation as closely as in the Patchawarra Trough, because there is only one stress indicator at this particular location.

Examination of the data surrounding the Cooper Basin suggests that the clockwise rotation of the $S_{\text{Hmax}}$ orientation from the
orientation in the Amadeus Basin to an east–west $S_{\text{Hmax}}$ orientation in parts of the Cooper Basin.

Northeast of the Cooper Basin, the $S_{\text{Hmax}}$ orientation is approximately north–northwest to south–southeast in the Bowen Basin (Fig. 2). The stress orientation in the Bowen Basin has been determined from engineering type (overcoring and hydraulic fracturing) in situ stress measurements. The engineering in situ stress data are particularly deep in terms of normal engineering data, going to a depth of 1 km, and are also very consistent when averaged over the entire basin (Hillis et al. 1999). The consistency of the stress orientation over a distance of 500 km in the Bowen Basin has led to the suggestion that this is a first-order stress trend (Hillis et al. 1999). Thus, the east–west $S_{\text{Hmax}}$ orientation in the eastern Cooper Basin appears to also rotate to an approximately north–south orientation in the Bowen Basin. Both Ramses-1 and Coonaberry-1, located in the northeastern corner of the study area, show a slight rotation to an east-northeast to west-southwest $S_{\text{Hmax}}$ orientation. However, the $S_{\text{Hmax}}$ orientation in the two wells only differs by approximately 10° from the $S_{\text{Hmax}}$ orientation in other nearby wells and, hence, is not as well defined as the rotation on the western side of the basin. A pre-existing borehole breakout to the northeast of the study area shows a significantly greater rotation than either Ramses-1 or Coonaberry-1 (Fig. 2). Consequently we feel the $S_{\text{Hmax}}$ orientations in Ramses-1 and Coonaberry-1 indicate the start of the large-scale rotation of the stress field from east–west in the central Cooper Basin to the north–south $S_{\text{Hmax}}$ orientation observed in the Bowen Basin. Nonetheless, further stress data are required on the eastern side of the basin to confirm the extent and nature of the stress rotation. Thus, the stress field in the Cooper Basin appears to mark the apex of a horseshoe-shaped rotation in the $S_{\text{Hmax}}$ direction across central eastern Australia. Furthermore, the mean $S_{\text{Hmax}}$ orientation (101° N) for the Cooper Basin is perpendicular to the direction of absolute plate velocity.

The Flinders Ranges, directly south of the Cooper Basin, is characterized by a mean $S_{\text{Hmax}}$ orientation of 088° N (Hillis & Reynolds 2000; Fig. 2). The Flinders Ranges is one of the most seismically active areas in Australia and, as a consequence, all of the stress indicators in the Flinders Ranges are from earthquake focal mechanism. The stress field in the Flinders Ranges is particularly scattered, which is probably the result of earthquakes occurring along pre-existing planes of weakness. Despite the scattered in situ stress measurements, the regional stress field in the Flinders Ranges appears to be consistent with that of the Cooper Basin. An east–west $S_{\text{Hmax}}$ orientation has also been recorded for the Perth region, located in southwestern Australia (Reynolds & Hillis 2000; Fig. 2). Hence the southern section of Australia, which includes the Perth region, Flinders Ranges and Cooper Basin, is characterized by a broadly east–west $S_{\text{Hmax}}$ orientation.

In southeastern Australia the stress field rotates from the east–west in the Cooper Basin and Flinders Ranges to a southeast–northwest $S_{\text{Hmax}}$ orientation in the Otway and Gippsland basins (Fig. 2). The $S_{\text{Hmax}}$ orientations in the Otway and Gippsland basins are both consistent and are thought to represent first-order stress trends (Hillis & Reynolds 2000). East of the Cooper Basin, the Sydney Basin has a particularly scattered stress trend and is thought to display the influence of local sources of stress rather than large-scale tectonic sources (Hillis et al. 1999).

5 IMPLICATIONS FOR PLATE BOUNDARY FORCES

The Australian intraplate stress field provides a unique opportunity to investigate the forces acting along the boundaries of the

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Recent finite element modelling of the IAP has used a new basis-set approach, which searches over a wide range of plate boundary combinations and calculates the misfit between the modelled and the observed stress fields (Reynolds et al. 2002). An observed regional stress field based on observations in 12 stress provinces provided an observed regional stress field based on observations in 12 stress provinces provided.
constraint for the modelling (Reynolds et al. 2002). The new modelling has demonstrated that the regional stress field in continental Australia can be accounted for by a combination of the principal tectonic forces acting on the plate (Reynolds et al. 2002).

Regional stress orientations in the western half of the Australian continent can be accounted for by combining a ridge push force along with a compressional force on the Himalayan and New Guinea boundaries (Coblentz et al. 1995, 1998). Application of these forces on the IAP causes the stress field to be focused orthogonal to the Himalayan and New Guinea boundaries with the stress field rotating between the two boundaries. Hence, an east–west $S_{\text{Hmax}}$ orientation is produced in the Perth and Carnarvon basins rotating to northeast–southwest in the Canning and Bonaparte basins and north–south in the Amadeus Basin. Modelling the observed regional stress field in the eastern half of Australia required compressional forces along the Solomon, New Hebrides, Tonga–Kermadec, New Zealand and southwest in the Canning and Bonaparte basins and north–south in the Amadeus Basin. Modelling the observed regional stress field in other areas of eastern Australia, such as the eastern half of Australia requires compressional forces along the Tonga–Kermadec subduction zone and modelled stress field in other areas of eastern Australia, significantly influences the Cooper Basin stress orientation. Thus, current modelling cannot fully match the horseshoe-shaped rotation in central eastern Australia using either plate-scale or regional sources of stress.

Results from the modelling indicate that the mean east–west $S_{\text{Hmax}}$ orientation in the Cooper Basin can be modelled using a range of plate boundary force combinations. Thus, no single plate boundary alone controls the stress orientation in the Cooper Basin. The east–west $S_{\text{Hmax}}$ orientation can be achieved in the Cooper Basin by balancing the forces acting on the northeast and southeast boundaries of the plate. The Tonga–Kermadec subduction zone, directly to the east of Australia, significantly influences the Cooper Basin stress field (Fig. 7). Large compressional forces applied at the Tonga–Kermadec boundary produce an east–west $S_{\text{Hmax}}$ in the Cooper Basin, however this also creates a large misfit between the observed and modelled stress field in other areas of eastern Australia, such as the Bowen Basin. Large tensional forces applied at the Tonga–Kermadec boundary, as modelled by Cloetingh & Wortel (1986), result in a north–south $S_{\text{Hmax}}$ orientation in the Cooper Basin and also over most of eastern Australia. Moderate compressional forces along the Tonga–Kermadec subduction zone result in the best fit to the observed stress field in the Cooper Basin. Moderate tensional forces along the Tonga–Kermadec subduction zone can fit the

### Table 2. List of wells containing DITFs. Depth and lengths are in metres. Azi = circular mean azimuth of $S_{\text{Hmax}}$; SD = circular standard deviation; Q = quality.

<table>
<thead>
<tr>
<th>Well Location</th>
<th>Log No.</th>
<th>Depth</th>
<th>Unweighted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lat.</td>
<td>Long.</td>
<td></td>
</tr>
<tr>
<td>Barina-1</td>
<td>−28.301</td>
<td>139.917</td>
<td>FMS 6</td>
</tr>
<tr>
<td>Bartilla-1</td>
<td>−28.252</td>
<td>139.878</td>
<td>FMS 85</td>
</tr>
<tr>
<td>Big Lake-54</td>
<td>−28.224</td>
<td>140.341</td>
<td>FMS 22</td>
</tr>
<tr>
<td>Brolga-3</td>
<td>−27.584</td>
<td>140.008</td>
<td>FMS 5</td>
</tr>
<tr>
<td>Bulveroo-1</td>
<td>−27.839</td>
<td>140.577</td>
<td>FMS 32</td>
</tr>
<tr>
<td>Caladan-1</td>
<td>−28.218</td>
<td>139.924</td>
<td>FMS 17</td>
</tr>
<tr>
<td>Cowan-3</td>
<td>−28.317</td>
<td>140.043</td>
<td>FMS 21</td>
</tr>
<tr>
<td>Dinkala South-1</td>
<td>−28.527</td>
<td>140.043</td>
<td>FMS 21</td>
</tr>
<tr>
<td>Dorodillo-1</td>
<td>−28.157</td>
<td>139.976</td>
<td>FMS 2</td>
</tr>
<tr>
<td>Dorodillo-3</td>
<td>−28.129</td>
<td>139.958</td>
<td>FMS 3</td>
</tr>
<tr>
<td>Dulingari-47</td>
<td>−28.110</td>
<td>140.89</td>
<td>FMS 54</td>
</tr>
<tr>
<td>Dullingari North-8</td>
<td>−28.088</td>
<td>140.858</td>
<td>FMS 58</td>
</tr>
<tr>
<td>Farina-2</td>
<td>−28.290</td>
<td>139.922</td>
<td>FMS 2</td>
</tr>
<tr>
<td>Fly Lake-8</td>
<td>−27.653</td>
<td>139.936</td>
<td>FMS 2</td>
</tr>
<tr>
<td>Gidgealpa-55</td>
<td>−28.038</td>
<td>140.001</td>
<td>FMS 2</td>
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<tr>
<td>Jena-12</td>
<td>−28.503</td>
<td>140.312</td>
<td>FMS 1</td>
</tr>
<tr>
<td>Malgomoa-3</td>
<td>−28.129</td>
<td>139.619</td>
<td>FMS 9</td>
</tr>
<tr>
<td>Merrimelia-30</td>
<td>−27.728</td>
<td>140.185</td>
<td>FMS 12</td>
</tr>
<tr>
<td>Merrimelia-32</td>
<td>−27.736</td>
<td>140.178</td>
<td>FMS 2</td>
</tr>
<tr>
<td>Moomba-73</td>
<td>−28.018</td>
<td>140.256</td>
<td>FMS 14</td>
</tr>
<tr>
<td>Moomba-78</td>
<td>−28.074</td>
<td>140.323</td>
<td>FMS 64</td>
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<tr>
<td>Mudiallee-5</td>
<td>−28.301</td>
<td>140.546</td>
<td>FMS 25</td>
</tr>
<tr>
<td>Nappacoongee East-1</td>
<td>−28.026</td>
<td>140.781</td>
<td>FMS 136</td>
</tr>
<tr>
<td>Naroomowie-4</td>
<td>−28.490</td>
<td>140.715</td>
<td>FMS 25</td>
</tr>
<tr>
<td>Pondrinnie-9</td>
<td>−27.563</td>
<td>140.651</td>
<td>FMS 4</td>
</tr>
<tr>
<td>Woooloo South-1</td>
<td>−28.285</td>
<td>140.040</td>
<td>FMS 2</td>
</tr>
<tr>
<td>Yalchirric-1</td>
<td>−27.543</td>
<td>140.578</td>
<td>FMS 5</td>
</tr>
</tbody>
</table>
observed stress field in the Cooper Basin. However, this results in a poorer fit between the modelled and observed stress fields in the rest of Australia, particularly throughout Western Australia.

The IAP is overriding the Pacific Plate along the Tonga–Kermadec subduction zone, with backarc spreading occurring on the IAP side. This suggests the existence of tensional forces related to the Tonga–Kermadec subduction zone. However, the in situ stress data in eastern and central Australia indicate a reverse fault stress regime, which is incompatible with large tensional forces at the Tonga–Kermadec subduction zone. Hence, we conclude that tensional forces associated with backarc spreading are not transmitted into the plate interior. We propose that the majority of the tensional forces associated with the Tonga–Kermadec subduction zone are accommodated along the numerous spreading centres within the Lau–Havre backarc basin. Furthermore, the use of a single tectonic plate to model the Australian stress field is an oversimplification, particularly in the Lau–Havre trough, which was recently subdivided into three additional plates, the Tonga Plate, the Kermadec Plate and the Niuafo'ou Plate (Zellmer & Taylor 2001; Bird 2003).

When the modelled stress field is constrained to the Australian regional stress field without using the mean east–west $S_{\text{Hmax}}$ orientation in the Cooper Basin, a north–south $S_{\text{Hmax}}$ orientation is predicted for most of central and eastern Australia (Fig. 9). This stress field is incompatible with the majority of scattered in situ stress data throughout southeastern Australia, which indicate $S_{\text{Hmax}}$ orientations between east–west and southeast–northwest (Fig. 2). However, the scattered stress data are not used to constrain the modelling. Hence, the average east–west $S_{\text{Hmax}}$ orientation in the Cooper Basin also improves the fit between the modelled and observed stress fields over much of southeastern Australia.

Throughout most of the best-fitting models the stress field in the Cooper Basin and the surrounding region is relatively isotropic ($S_{\text{Hmax}} = S_{\text{hmin}}$) in comparison with the rest of Australia (Fig. 8). However, the relatively consistent east–west $S_{\text{Hmax}}$ orientation determined from the observed stress data indicates that the stress field in the Cooper Basin is particularly anisotropic (i.e. $S_{\text{Hmax}} \gg S_{\text{hmin}}$). The co-occurrence of both borehole breakouts and DITFs in many Cooper Basin wells confirms this stress anisotropy. This discrepancy between the magnitude of the observed and modelled stress fields also indicates the Cooper Basin may be influenced by a regional source of stress not included in the plate-scale modelling.

Table 3. Summary of well average $S_{\text{Hmax}}$ azimuth for the Cooper Basin.

<table>
<thead>
<tr>
<th>Indicator type</th>
<th>Quality</th>
<th>Number</th>
<th>Azimuth</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breakout</td>
<td>A–C</td>
<td>47</td>
<td>100°N</td>
<td>17°</td>
</tr>
<tr>
<td>DITF</td>
<td>A–C</td>
<td>17</td>
<td>104°N</td>
<td>17°</td>
</tr>
<tr>
<td>Breakout + DITF</td>
<td>A–C</td>
<td>64</td>
<td>101°N</td>
<td>19°</td>
</tr>
</tbody>
</table>

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6 LOCAL SOURCES OF STRESS IN THE COOPER BASIN

While the observed stress orientations in the Cooper Basin are reasonably consistent, a number of smaller-scale stress perturbations cannot be accounted for by modelling using either large-scale tectonic forces or regional sources of stress. These local features include variable stress orientations in isolated wells that differ significantly from the regional stress orientation in a particular area (e.g. Cowan-3 and Challum-9, 10 and 12). Identifying the source of local stress variations (orientations and magnitudes) is often problematic as a result of the poor resolution in the stress/structural data sets and the number of effects that may be superimposed.

Local stress perturbations are the consequence of structure and/or the lateral variations in the elastic properties of rocks (Bell 1996). Numerous studies have explained perturbations in the regional stress field resulting from the presence of geological structures (e.g. Aleksandroski et al. 1992; Yale et al. 1994; Dart et al. 1995) and crustal density heterogeneities (e.g. Mareschal & Kuang 1986; Assameur & Mareschal 1995; Mandal et al. 1997). Variation in the elastic properties of the rocks can affect the stress field in two ways. If a body of rock is relatively harder than the surrounding rock then the $S_{Hmax}$ orientation intersects the interface at right angles (Bell 1996). Alternatively, if a body of rock is relatively softer than the surrounding rock then the $S_{Hmax}$ orientation parallels the interface (Bell 1996). The degree to which the stress field is perturbed relates to the contrast in geomechanical properties at the interface (Zhang et al. 1994). Stress perturbations also occur as a result of slip on pre-existing faults in rocks with homogenous elastic properties. In this situation, the stress perturbations are greatest at the tips of the discontinuity and can vary as a result of factors such as the differential stress magnitude, the friction coefficient on the discontinuity and the strike of the discontinuity relative to the far-field stress (Homberg et al. 1997).

The $S_{Hmax}$ orientations interpreted from the three Challum wells are the only stress perturbation that can be confidently linked to a geological structure in the basin. All three wells show a consistent $S_{Hmax}$ orientation that parallels a nearby basement fault (Fig. 5). The $S_{Hmax}$ orientation determined for the three wells is rotated $20^\circ - 30^\circ$ in a clockwise direction compared to the $S_{Hmax}$ orientation in the nearest wells to the east. Fault parallel stress orientations have been observed in a number of studies (Aleksandroski et al. 1992; Yale et al. 1994). The stress rotation observed in the Challum wells is the same as that predicted by 2-D distinct element modelling of a discontinuity previously conducted by Homberg et al. (2004) and Homberg et al. (1997). The 2-D modelling shows the orientation of the local stress perturbation closely parallels the fault orientation along the mid-section of the fault in situations where there is a small angle between the $S_{Hmax}$ orientation and the fault (Homberg et al. 1997; Fig. 10). Also, a high differential stress is required in order to match the fault parallel stress perturbations (Homberg et al. 1997), consistent with observations in the Cooper Basin. The maximum stress perturbation is modelled to occur at the extensional zones (Homberg et al. 1997), which are located on the southern side of the
western tip of the fault and the northern side for the eastern tip of the fault for the example presented in this study (Fig. 10). However, no stress data exists at either tip of the fault to verify if this is the case.

Another major stress perturbation is observed in Cowan-3, located in the southeast corner of the basin. A large number of consistently oriented DITFs are present in Cowan-3 indicating a 063°N \( S_{\text{Hmax}} \) orientation. In comparison, the Barina-1 well, which is approximately 12 km to the west, has consistently oriented DITFs indicating a 108°N \( S_{\text{Hmax}} \) orientation. The available structural data indicate no major basement-cutting faults close to Cowan-3 (Fig. 5). Cowan-3 is however, located near one of three large Carboniferous granite bodies that have been intersected in more than 23 wells in the Nappamerri Trough (Gatehouse et al. 1995; Fig. 1). The granite bodies are characterized by a pronounced negative Bouguer gravity anomaly. Other granite bodies are assumed to exist within the basin on the basis of the gravity signature, however they are too deep to be reached by drilling (Fig. 1). The \( S_{\text{Hmax}} \) orientation at Cowan-3 rotates perpendicular to the granite body, oblique to adjacent wells and is consistent with the granite being stiffer than the surrounding rocks. However, a number of the other wells (Moomba-73, Moomba-78, Big Lake-54 and Bulyeroo-1), which are also close to the granite bodies, exhibit an east–west \( S_{\text{Hmax}} \) stress orientation and appear unperturbed by the granite bodies. It should be noted that the effect of the granite body at Moomba-73 could not be assessed, as the regional east–west \( S_{\text{Hmax}} \) orientation is perpendicular to the granite body. Because the other wells close to the granite bodies are unperturbed, we feel the stress rotation in Cowan-3 is probably a result of an unidentified fault or local variations in the rock elastic properties not yet identified.

7 CONCLUSIONS

Borehole breakouts and DITFs from 61 wells in the Cooper Basin indicate an average \( S_{\text{Hmax}} \) orientation of 101°N (A–C quality data). A total of 890 borehole breakouts and 608 DITFs were interpreted in the Cooper Basin. The average \( S_{\text{Hmax}} \) orientation is consistent between different data types and different data quality. The mean east–west \( S_{\text{Hmax}} \) orientation determined for the Cooper Basin is orthogonal to the direction of absolute plate velocity for the IAP. Within the Cooper Basin a significant stress rotation occurs from the east–west \( S_{\text{Hmax}} \) orientation in the Nappamerri Trough, and much of the basin, to northwest–southeast \( S_{\text{Hmax}} \) orientation in the Patchawarra Trough. This rotation is part of a larger scale horseshoe-shaped stress rotation across central eastern Australia between the Amadeus, Cooper and Bowen basins.
Figure 8. Best-fitting plate boundary force model displaying the predicted stresses across continental Australia from Reynolds et al. (2002). The predicted stress orientations were constrained using all 12 stress provinces (including the Cooper Basin) defined in Reynolds et al. (2002).

Figure 9. Best-fitting plate boundary force model determined when excluding the east–west $S_{\text{Hmax}}$ orientation in the Cooper Basin to constrain the model.

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Finite element modelling of the in situ stress field of the IAP using a range of plate-scale tectonic forces is able to match the $S_{\text{Hmax}}$ orientation over most of Australia reasonably well, including the mean east–west $S_{\text{Hmax}}$ orientation in the Cooper Basin. However, plate boundary–scale modelling cannot adequately match the horseshoe-shaped stress rotation between the Amadeus, Cooper and Bowen basins. A large combination of plate boundary forces can be used to match the mean east–west $S_{\text{Hmax}}$ orientation in the Cooper Basin. Nonetheless, the Cooper Basin stress field suggests that stresses from tensional forces acting along the Tonga–Kermadec subduction zone are not transmitted into the interior of the Australian Plate. More in situ stress data are required in the areas to the northeast and northwest of the Cooper Basin in order to improve the plate-scale modelling and further account for the horseshoe-shaped stress rotation. A number of smaller scale stress features have been identified within the in situ stress data that cannot be explained by plate-scale tectonic forces. These features are possibly a result of local geological structure and/or density contrasts perturbing the stress field.

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