Understanding natural fracture networks is becoming increasingly important to the geothermal industry due to their control on subsurface porosity and permeability. To understand fluid flow in a natural fracture network in a basin at present day, it is vital to determine the in-situ stress regime. Previous studies have shown that fluid flows in the direction of the maximum horizontal stress ($\sigma_H$; Heffer & Lean, 1993). However, natural fracture networks can be more complex than this. Therefore, it is vital to map them at all scales to understand their connectivity and potential fluid flow pathways.

Faults and fractures trending approximately NW-SE and NE-SW in the Cooper Basin and N-S and NW-SE in Northern Perth Basin have been identified using image logs. In-situ stress analysis demonstrates that these faults and fractures are optimally oriented for reactivation and are thus, open to fluid flow. However, the fault and fracture networks are not visible on the amplitude seismic data, making fracture connectivity and potential fluid flow pathways difficult to map and model. Here, we use analysis of the seismic attributes from three-dimensional seismic cubes in the Cooper and Northern Perth basins to identify and map these fault and fracture networks. In both the Cooper and Northern Perth basins, seismic attribute mapping has demonstrated good connectivity between the optimally oriented faults and fractures, and thus, providing excellent fluid flow pathways within the basins.

Keywords: In-Situ Stress, Seismic Attributes, Fractures, 3D Mapping, Cooper Basin, Northern Perth Basin, Fluid flow

Geological setting of the Cooper and Northern Perth Basin

The Warburton, Cooper, Eromanga and Eyre basins are successive stacked basins located in central-eastern Australia separated by two major unconformities (Figure 1). The Late-Carboniferous to Middle-Triassic Cooper Basin is composed of non-marine, characterized by fluvial, lacustrine and swamp deposits with coal measures (Hill and Gravestock, 1995; Alexander, 1998; Van Ruth et al., 2003).

The Perth Basin is located in southern Western Australia. It is a N-S trending rift basin, extending approximately 1000 km from north to south and is both onshore and offshore (Figure 1). The basin displays two major phases of rifting and subsequent infill from the Late Carboniferous to Early Permian, in both onshore and offshore parts of the Northern Perth Basin (Mory & Iasky, 1994; Quaife et al., 1994; Song & Cawood, 2000; Hodge, 2005).

Elevated heatflows are observed in both basins. In the Cooper Basin these heat flows are associated with basement granites, possible from the Mount Painter Suite. Combined with the presence of natural fracture networks and extensive petroleum exploration data, these factors make the Cooper and Northern Perth basins significant geothermal prospects.

In-Situ Stress Analysis

The three principal stresses ($\sigma_1 > \sigma_2 > \sigma_3$) can be resolved into a vertical stress ($\sigma_v$) and two horizontal stresses (a maximum, $\sigma_H$, and a minimum, $\sigma_h$) within the Earth’s crust (Anderson, 1951). The orientations and magnitudes of these three stresses control the orientation of newly forming fractures and the reactivation of pre-existing fractures. The in-situ stress tensor for a given region can be defined using borehole failure observed on image logs, as well as density logs and leak-off tests (LOTs).

Borehole breakouts are stress-induced elongations of a borehole cross-section (Figure 2b), which occur when the maximum circumferential stress exceeds the compressive rock strength; resulting in spalling of the borehole.
wall (Bell, 1996a; Bell, 1996b). Borehole breakouts occur perpendicular to the present-day $\sigma_H$ orientation (Kirsch, 1898; Bell & Gough, 1979; Figure 2b). On electrical resistivity images produced from FMI logs borehole breakouts appear as dark, electrically conductive areas separated by 180° (Figure 2c).

Drilling-induced tensile fractures form when the minimum circumferential stress becomes tensile (i.e. negative) and exceeds the tensile strength of the borehole wall (Peška & Zoback, 1995; Brudy & Zoback, 1999; Figure 2b). Such DITFs are parallel to the present-day $\sigma_H$ orientation in vertical wells. On image logs DITFs appear as dark electrically conductive fractures, usually not longer than 2.0 m, often with small jogs or kinks and separated by 180° (Brudy & Zoback, 1999).

### In-situ stress magnitudes in the Cooper and Northern Perth basins

The magnitude of $\sigma_v$ was calculated by integration of density logs from petroleum wells. The vertical stress magnitude at a specific depth is equivalent to the pressure exerted by the weight of the sediment overburden, and water column for offshore wells (Engelder, 1993).

The magnitude of $\sigma_h$ was calculated using leak-off tests (LOTs) and formation integrity tests (FITs). The tests involve increasing the pressure of the borehole fluid in a small section (<10 ft) of newly drilled wells, immediately after the casing has been set (Dickey, 1986). During the test, the pressure is increased until a fracture has formed at the borehole wall (Dickey, 1986). Fracture formation is marked by a change in slope on a pressure versus time plot. In most cases the fracture forms in the direction of $\sigma_H$ and opens against (orthogonal to) $\sigma_h$. Leak-off test pressures provide the best estimate of $\sigma_h$ (Bell, 1996b).

![Figure 2: Northern Perth Basin: a) HDT logs exhibiting borehole breakouts (Reynolds & Hillis, 2000). b) A cross-section of a borehole illustrating the position of borehole breakout and DITFs relative to present-day $\sigma_{\text{max}}$ in a vertical wellbore. c) FMI image from Kingia-1 showing borehole breakout and DITFs separated by 90° around the borehole wall. Note the gamma ray corresponds to the position of borehole breakouts and DITFs; borehole breakouts are confined to low gamma ray (<100 gpi) horizons and DITFs to high gamma ray (>100 gpi) horizons. From King et al., 2008.](image)

### Maximum horizontal stress orientations in the Cooper and Northern Perth basins

Previous studies of the present-day stresses in the Cooper Basin and Northern Perth Basin used high resolution dipmeter logs and image logs (Reynolds & Hillis, 2000; Reynolds et al., 2004; King et al., 2008). In this study, image logs from a further 5 petroleum wells in the Cooper Basin have been analysed demonstrating a mean regional $\sigma_H$ orientation in the Cooper Basin is approximately E-W at ~100. In the Northern Perth Basin, a further 8 petroleum wells have been analysed; demonstrating 302 BOs and 75 DITFs, giving an E-W $\sigma_H$ orientation, at ~080.

### Table 1: In-situ stress magnitudes in the Cooper and Northern Perth basins

<table>
<thead>
<tr>
<th>Vertical Stress</th>
<th>Maximum Horizontal Stress</th>
<th>Minimum Horizontal Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooper Basin at 1 km depth</td>
<td>17.0-20.4</td>
<td>26.9</td>
</tr>
<tr>
<td>Cooper Basin at 3 km depth</td>
<td>54.1-65.1</td>
<td>79.2</td>
</tr>
<tr>
<td>Northern Perth Basin at 1 km depth</td>
<td>21.1-22.8</td>
<td>22.5</td>
</tr>
<tr>
<td>Northern Perth Basin at 3 km depth</td>
<td>69.1-69.6</td>
<td>71.0</td>
</tr>
</tbody>
</table>

In the Cooper Basin, the magnitude of $\sigma_H$ was constrained by ‘Frictional Limits’, which gives an upper limit to possible values of $\sigma_H$ (Jaeger & Cook, 1979). The magnitude of $\sigma_H$ was calculated in the Northern Perth Basin using the relationship between $\sigma_h$ and $\sigma_H$ in the presence of DITFs, including the pore pressure (Pp) and mud weight (Pw; after Brudy & Zoback, 1999).

The stress magnitudes in the Cooper Basin and Northern Perth Basin broadly define strike-slip fault stress regimes ($\sigma_H > \sigma_v > \sigma_h$), consistent with previous studies. However, the magnitude of $\sigma_h$, approaches $\sigma_v$ inferring that the stress regimes are transitional between strike-slip fault and reverse fault ($\sigma_H > \sigma_v \approx \sigma_h$) in both of the basins; consistent with previous studies (King et al., 2008; Reynolds et al., 2004; Reynolds et al., 2006).
Observed natural fractures in the Cooper and Northern Perth basins

Natural fractures were interpreted on the image logs in the Northern Perth Basin and Cooper Basin. Natural fractures are distinguished from DITFs on image logs by their continuous nature; natural fractures are often seen as continuous sinusoids whereas DITFs are discontinuous because they only propagate in the tensile region of the borehole wall (hence separated by 180°; Barton, 2000). Where DITFs are always electrically conductive, natural fractures can be both electrically conductive and resistive (Barton, 2000).

In this study both electrically conductive fractures and electrically resistive fractures were observed on FMI and FMS logs from the Northern Perth Basin and Cooper Basin (Figures 3 and 4). Conductive fractures are considered to be open and filled with drilling mud, giving them a dark, electrically conductive appearance on FMI images. Resistive fractures are thought to be closed and/or cemented producing the light, electrically resistive appearance on FMI images.

Wells analysed for natural fractures in the Cooper Basin demonstrate conductive fractures striking NE-SW and NW-SE, forming a conjugate set (Figure 3; Backé et al., 2010). A second smaller E-W striking set is also observed in the Cooper Basin (Backé et al., 2010).

In the Perth Basin electrically resistive and conductive fractures closely parallel observed N-S to NW-SE striking fault sets and E-W striking faults (King et al., 2008). Resistive fractures are observed in all three orientations. Conductive fractures are only observed to strike N-S and NW-SE (Figure 4).

Prediction of fluid flow through natural fractures

The formation of new faults and fractures and reactivation of pre-existing faults and fractures is controlled by the in-situ stress regime. In a strike-slip fault stress regime new faults and fractures form approximately 26-30° to \(\sigma_H\) (Anderson, 1951; Healy et al., 2006).

A transitional reverse fault to strike-slip fault stress regime is inferred in both the Cooper and Northern Perth basins. Figure 5 is a fracture susceptibility plot demonstrating a transitional reverse fault to strike-slip fault stress regime (\(\sigma_H > \sigma_V \approx \sigma_H\)) at 1 km depth and an E-W \(\sigma_H\) azimuth, consistent with the two basins. Reactivation potential plots use the same principals as Mohr Circles (e.g. Means, 1976) to assess which orientations of pre-existing faults and fractures are most likely to be critically stressed, and therefore, most likely to be active and open to fluid flow. Red areas on the diagram illustrate the orientations of faults and fractures (poles to planes) most susceptible to reactivation and blue areas exhibit fault and fracture orientations least likely to reactivate (closed to fluid flow). Pre-existing faults and fractures that strike N-S and have horizontal or vertical to steep dips are the least prone to reactivation in the two basins (Figure 5). However, fractures striking N-S, NW-SE and NE-SW with moderate dips are the most prone to reactivation in the two basins. Therefore, the N-S, NE-SW and...
NW-SE fractures are thus, most likely to be open to fluid flow (Figure 5).

Here we have demonstrated the use of the in-situ stress regime to understand the potential for fluid flow through pre-existing fractures observed on image logs in the Cooper and Northern Perth Basins. However, natural fracture networks are often more complex. The limitations associated with interpreting natural fractures on image logs are: 1) coverage controlled by well location; 2) all observations are at a metre-scale, and; 3) wells only provide two-dimensional visualisation of the fracture network. In this study we use seismic attribute mapping to develop our models of the natural fracture networks in the Cooper and Northern Perth basins.

Three-Dimensional Seismic Mapping

Different techniques based on either structural or on geophysical methods can be used to improve the interpretation of seismic data, whether 2D or 3D. Calculating, displaying and interpreting seismic attributes have been a large component for any geophysicist toolbox for the past couple of decades. For detecting potential fractures at depth in both the Cooper and North Perth Basins, we followed a three-step methodology, using the OpenDetect™ software. First, a steering cube of the dip of the seismic events in inline and crossline direction at every sample point was created from the amplitude cube using the Fast Steering algorithm, later filtered by a median filter (Fig. 6). This steering cube is the base for the structural oriented filtering of seismic volumes, enhancing multitrace attributes and eventually curvature attribute generation. The attributes calculated from the dip-steering cube are guided along a three dimensional surface on which the seismic phase is approximately the same. The dip/azimuth information stored in the steering cube is used to create a virtual horizon at each position, thus effectively filtering the data from noise when used in conjunction with a median filter. This allows the removal of random noise in the dip steering cube, and enhances laterally continuous seismic events by filtering noise along the structural dip. In median filtering, the centre amplitude in a dip-steered circle is replaced by the median amplitude within the extraction volume; the effect is an edge-preserving smoothing of the seismic data.

Finally, several volumetric dip-steered-curvature attributes were computed from the seismic volume and the dip-steering volume, following the method of Al-Dossary and Marfurt (2006). This method uses a sub-volume of data to compute the curvature at every point in the 3D seismic cube, in multiple wavelengths. Shorter wavelengths denote intense and highly localized fracture patterns and longer wavelengths correspond to broader fractures.

Natural fracture networks in the Cooper Basin

This study, using both seismic amplitude and attributes mapping, allowed us to map and to better constrain the structure and the natural fracture network in the region covered by the 3D seismic cubes in the Cooper and Northern Perth basins.

The Cooper Basin is affected by numerous structures of various scales. At the levels of the Roseneath and Murteree Shale Formations, to the southeast of the study area is the regional-scale Moomba-Big Lake fault, trending SW-NE. This high-angle fault is dipping to the southeast, with the folded hanging-wall being uplifted by roughly 0.1s to 0.2s. A series of more spatially limited folds also appear in the footwall of the Moomba-Big Lake fault, away from the fault itself. These folds appear to be symmetrical in section-view, and present generally four-way closure geometries in map view. The top of the Cooper Basin sediments is a regional unconformity, which also marks a boundary in the deformation style. Above at this level, the beds appear less deformed, with some very subtle low amplitude folds of kilometric-scale.
A clear pervasive fabric is evidenced by the most positive curvature attribute (Fig 6), but remains invisible on the amplitude time slices or extraction along the horizons. This fabric consists of linear features with various lengths, mainly orientated along two directions, NW-SE and SW-NE. These fabrics are visible on time slices between the 1.7s and 2.2s, as well as along the horizon extraction maps. The density of this fabric is variable on both the Roseneath and the Murteree Shales. It appears that this fabric is generally denser close to the faults and at the apex of the mapped folds. However, other areas characterized by a low intensity of deformation also display a strong fabric as well. A drawback of this analysis is the potential limited detection of the acquisition footprint, reducing the resolution and scale of the fracture analysis.

This pervasive fabric displayed using the seismic processing and imaging techniques is parallel to the fractures observed on image logs in the Cooper Basin. It is therefore possible that the seismic attributes display actual fractures. This approach is currently being applied in the Northern Perth Basin, which we suggest will display a similar correlation with fractures mapped using image logs.

**Summary**

Different methods, valid for different observation scales, can be used to characterise in-situ stress and natural fracture networks. In this work, we have focussed on well-derived data, such as geophysical logs, and three-dimensional seismic data.

The Cooper Basin is a Late-Carboniferous to Middle-Triassic intraplate sag basin. The maximum horizontal stress orientation has been determined using image logs at ~100. Stress magnitudes in the Cooper Basin demonstrate a transitional strike-slip fault to reverse fault stress regime. Conjugate natural fractures striking NW-SE and NE-SW are considered to be active and open to fluid flow in this present-day stress regime. Seismic attribute mapping has identified a structural fabric in the same orientation as these fractures. Thus, implying good connectivity between these open fractures and numerous potential fluid pathways.

The Northern Perth Basin is part of the larger Late-Carboniferous to Early-Permian rift basin. The maximum horizontal stress orientation has been determined using image logs at ~084. Stress magnitudes in the Northern Perth Basin demonstrate a transitional strike-slip fault to reverse fault stress regime. Natural fractures striking N-S and NW-SE are considered to active and open to fluid flow in this present-day stress regime.

For completeness, the description of the fracture network should be combined with direct observation along oriented core and field work. However, this study demonstrates the importance evaluating both seismic data and well log data to understand in-situ stresses and the associated fracture networks where these direct data are not available.

**References**


Jaeger & Cook, 1979


