Natural fracture characterisation in a coal measure succession: an analogue for coal seam methane and tight gas reservoirs

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Abstract

Reliable characterisation of natural fracture networks can improve management of tight gas reservoirs typical of onshore Australia. However, characterisation of natural fracture networks in tight gas reservoirs is often hindered due to poor sample availability (i.e. limited core and image logs) and the absence of quality outcrop. The Goonyella Riverside coal mine in the northern Bowen Basin provides an analogue study for the development of natural fracture systems in a mildly thrusted Permian coal measure succession. A total of 3,862 m of image log data from 18 closely spaced wells was integrated with 3D seismic data and outcrop observations to characterise structural style and natural fracture development at Goonyella Riverside. Three distinct stages of fracturing are observed and linked to the structural evolution of the area: (i) coal cleats and compaction related normal faults formed during Late Permian burial and diagenesis, (ii) thrust faults and subsidiary low-angle shear fractures formed during the Early to Mid Triassic Hunter Bowen Orogeny and (iii) tensile joints formed during Cretaceous uplift and unloading. Different mechanical units including massive amalgamated distributary channel sandstone bodies, laminated overbank deposits and coal seams display distinct fracture development, defining the mechanical stratigraphy. Observations made in this study may be used to improve development drilling design and reservoir management in naturally fractured tight gas reservoirs of onshore Australia.

Keywords: fractures, mechanical stratigraphy, coal, Bowen Basin, thrust fault

Introduction

Effective characterisation of natural fracture networks in the subsurface is often hindered due to limited core and/or image logs and absence of quality outcrop. A coal mine was sought for this study to improve our understanding of natural fracture development in a coal measure succession and is intended as an analogue to assist development of low permeability reservoirs in the Bowen and Cooper Basins. The Goonyella Riverside open-cut and underground mine was selected for its comprehensive data-set including a 3D seismic survey, closely spaced wells with image log data and excellent exposure of structural features.

The BHP Billiton Mitsubishi Alliance (BMA)-operated Goonyella Riverside mine is located 30 km north of Moranbah and 190 km southwest of Mackay (Fig. 1). Goonyella Riverside is operated as an open-cut coal mine with an underground development in progress. The Goonyella Lower and Goonyella Middle coal seams dip 3-6º east and are mined from west to east in a series of open-cut pits up to 150 m deep that extend some 17 km from north to south (Fig. 1). The structures shown in Figure 1 have been mapped by BMA and CSIRO geologists from open-cut mapping and well data (Esterle & Sliwa 2002). The underground development will mine the Goonyella Middle Seam using the longwall method over an area approximately 2.5 X 3 km to depths in the order of 300 m. A 3D seismic survey and closely spaced wells with image log data were acquired by BMA over the underground area east of the open-cut to predict mining conditions and are combined with open-cut observations to form the data set for this study.

Figure 1. Location and layout of the BMA Goonyella Riverside coal mine showing the location of the underground development and 3D seismic survey (Esterle and Sliwa 2002).
Geological setting

Goonyella Riverside is in the northern Bowen Basin within the foreland of the fold and thrust belt developed during the Triassic Hunter-Bowen Orogeny. Goonyella Riverside is located on the east-dipping western limb of a regional syncline referred to as the Nebo Synclinorium (Fig. 1). Deformation in the area is typically mild, characterised by open folds and minor thrusting (Dickins & Malone 1973; Holcombe et al. 1997). The most significant structure in the area is the regional Jellinbah thrust fault system, some 15 km east of Goonyella Riverside (Fig. 1), formed at the end of the Hunter-Bowen Orogeny. The Jellinbah thrust fault is west-vergent and strikes approximately north–south with maximum throw in the order of 600–800 m (Esterle & Sliwa 2002). A series of subsidiary thrust faults with maximum throws in the order of 5 m are the most significant structural features at Goonyella Riverside. The faults are imaged as low amplitude trends by the 3D seismic survey and are exposed in outcrop (Figs 2, 3, 4). An inherent problem with such a study is that large structural features near the detection limit of petroleum seismic data (throw in the order of 10 m) create deleterious mining conditions and are thus avoided by the coal mining industry. The largest faults encountered at Goonyella Riverside have maximum throw of approximately 5 m which is at or below typical detection limits of petroleum seismic data. It is therefore difficult to directly relate/upscale structural observations made in coal mine studies to most hydrocarbon systems due to scaling effects. However, many of the principles of deformation and fracturing at the coalmine-scale are expected to apply at the petroleum-scale.

The coal seams mined at Goonyella Riverside are part of the Late Permian Moranbah-German Creek coal measures. The coal measures are approximately 700 m thick and were deposited in response to the onset of Late Permian foreland loading prior to the Hunter-Bowen Orogeny (Fielding et al. 1995). The three main coal seams encountered at Goonyella Riverside are the Goonyella

Figure 2. Thrust fault exposed in the northern endwall of Goonyella Riverside. The top of the coal seam forms an effective detachment surface in the carbonaceous shale (CS) and siltstone (Si) sequence. Photo courtesy of BMA

Figure 3. Amplitude map of the base of the Goonyella Middle Seam (GMS) produced from the 3D seismic survey, faults appear as low amplitude trends. Wells with image log data are shown with white circles

Figure 4. East-west cross-line through borehole 40993. The coal seam dips 2–10° towards east. The thrust faults dip approximately 30° east and have maximum throw of ~5 m.

Figure 5. Wireline log suite from borehole 40996 showing the Goonyella Riverside stratigraphy. The gamma ray is on the left of the figure and increases from left to right. The density logs is on the right of the figure and increases from left to right. The sonic log is on the right of the figure and increase from right to left.
Lower Seam (GLS), the Goonyella Middle Seam (GMS) and the Goonyella Upper Seam (GUS). The main seams are up to 10 m thick with various splits and rider seams (Fig. 5). The coal seams are separated by a variety of clastic interburden comprising amalgamated fluvial distributary channel sandstones and floodplain sediments of fine-grained and thinly bedded sandstones, siltstones and shale. Two distinct sediment stacking patterns have created a coal-prone interval and a sand-prone interval. The coal-prone interval extends down from the top of the GMS, comprising thick coal seams separated by overbank clastic sediments. The sand-prone interval overlies the coal-prone interval comprising massive amalgamated channel sands separated by overbank clastic sediments (Figs 5, 6).

Figure 6. The highwall between ramp 4-6 in front of the development underlie immediately west of the 3D seismic survey (Fig. 1)viewed towards north-east. The three types of mechanical units are shown, coal seams, overbank and amalgamated distributary channels are coloured blue, green and red respectively. The highwall is approximately 70 m high.

Mechanical stratigraphy

The mechanical stratigraphy has considerable bearing on deformation and fracture development at Goonyella Riverside and is defined by a series of mechanical units. A mechanical unit is one or more stratigraphic units of relatively similar mechanical properties that deform and fracture independently of other units (Gross 1993; Odling et al. 1999; Underwood et al. 2003). Mechanical units are a function of their composition and thus their sedimentology. Detailed laboratory work as summarised in Table 1 shows that sandstone is the most competent and coal is the least competent lithology at Goonyella Riverside (Seedsman 1998).

Sequences deposited in different environments have varying proportions of sandstone, siltstone, shale and coal, thereby defining mechanical units. It is emphasised that a sequence with relatively similar mechanical properties comprising one or more stratigraphic units define a mechanical unit rather than each sedimentary unit (Underwood et al. 2003). A basic classification has been constructed for this study with three types of mechanical units defined by their composition (Figs 5, 6):

Table 1. Rock properties determined by geotechnical testing (Seedsman, 1998).

<table>
<thead>
<tr>
<th>Property</th>
<th>Sandstone</th>
<th>Siltstone</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.5 (0.1)</td>
<td>2.5 (0.1)</td>
<td>1.5 (0.2)</td>
</tr>
<tr>
<td>UCS (MPa)</td>
<td>45.9 (15.3)</td>
<td>36.0 (17)</td>
<td>9.3 (2.4)</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>11.5 (6.8)</td>
<td>8.2 (3.3)</td>
<td>3.4 (1.2)</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.34 (0.1)</td>
<td>0.30 (0.1)</td>
<td>0.36 (0.15)</td>
</tr>
<tr>
<td>Friction Angle</td>
<td>27.7º (3.1)</td>
<td>25.7º (6.3)</td>
<td>30º (4.3)</td>
</tr>
</tbody>
</table>

I. Coal units. These units comprise seams up to 10 m thick of banded coal with bright, vitrinite-rich and dull, inertinite rich layers and occasional thin stone bands in the order of 100 mm thick. A single coal seam may act as numerous individual mechanical units separated by bedding surfaces between the different coal types and thin stone bands.

II. Overbank units. These units crudely group together all rocks deposited in the overbank environment except coal, and consist of lobate crevasse-splay sand bodies and layered floodplain siltstone, shale and carbonaceous shale. A package of overbank facies may act as numerous mechanical units as thin as 100 mm.

III. Distributary channel units. These units consist of sandstone deposited in amalgamated distributary channels ranging from 5–40 m thick and typically behave as single, massive mechanical units. The sand-prone interval occurs above the GMS, comprising thick distributary channel units separated by overbank units. The coal-prone interval extends down from the top of the GMS and comprises thick coal seams separated from overbank units by effective slip surfaces (Fig. 2). Figure 6 shows the highwall immediately west of the underground development. The photo has been coloured according to the mechanical stratigraphy showing coal, overbank and distributary channel units.

Fracture observations: outcrop

The highwalls at Goonyella Riverside could not be mapped in detail due to occupational health and safety requirements. However, several different types of structures were observed in the mine workings and are used to constrain interpretation of the subsurface data.

I. Coal cleats were observed in all coal seams and are interpreted to have formed during Late Permian burial and diagenesis. Cleat development is variable and appears to be a function of the coal composition, as described by previous authors for Bowen Basin and other coals (Pattison et al. 1995; Laubach et al. 1998; Pashin 1998). Face cleat spacing in the bright vitrinite-rich layers is typically in the order of 5 mm. Face cleat spacing in the dull inertinite-rich layers is more variable ranging from 20–150 mm. The face cleats generally strike east-west +/- 10º and the butt cleats are arranged in an orthogonal pattern about the face cleats typically striking north-south +/- 20º. The butt cleats are less well developed and the spacing is more variable. The face and butt cleats are locally overprinted in damage zones around faults.

II. Thrust faults with maximum throw in the order of 5 m are the dominant structures at Goonyella Riverside (Fig. 2). The faults strike approximately north–south and are subsidiary structures to the regional Jellinbah fault, some 15 km east of Goonyella Riverside. The faults display a ramp-flat geometry and commonly detach along the coal-rock interface (Fig. 2). The faults are characterised by a fault zone of milled rock (cataclasite) in the order of a few mm thick and a damage zone comprising low-angle shear fractures of similar orientation to the thrust faults spaced in the order of 0.5–1 m (Fig. 7). The thrust faults and associated damage zones are significant hydraulic conduits within the in-situ stress field. The large thrust fault shown in Figures 3 and 4 accounted for almost half the groundwater entering the underground exploration adit (Callow & Briese 2002).

III. Several non-pervasive, moderately dipping normal faults (Fig. 8) were observed in the underground workings with maximum throw in the order of 1 m. The faults strike east–west +/- 20º and dip 45–70º. The faults offset the top
of the Goonyella Middle Seam and overlying units and appear to die out in the Goonyella Middle Seam. There appears to be only minor damage along the fault surface with some mulling of the coal seams in a very thin zone in the order of a few mm. The fault shown in Figure 8 is interpreted as an accommodation structure within the hangingwall of a larger thrust fault. Compaction-related normal faults occur beneath massive sand bodies (CNF; Fig. 9).

IV. Near vertical joints are the youngest structural features at Goonyella Riverside. The joints have hackle and plume surface ornamentation characteristic of tensile failure. No mineralisation was noted in any of the joints observed. The dominant joint set strikes east–west +/- 20° with a minor northwest–southeast striking set. The mechanical stratigraphy controls joint occurrence, height and spacing. Joint spacing generally appears proportional to joint height in most of the exposures in the open-cut and underground workings with spacing to height ratios in the range 0.7–1 (Fig. 9). The joint sets are similar to those described by various authors for layered sedimentary sequences throughout the world interpreted as a response to horizontal tensile stresses created by minor expansion during uplift and unloading (Engelder 1985; Price & Cosgrove 1990; Becker & Gross 1996). The timing of joint development at Goonyella Riverside is poorly constrained but is interpreted to be related to Cretaceous uplift and unloading (Esterle & Sliwa 2002). Joints are typically well developed in the amalgamated channel units and in sandstone lenses within the overbank units and are either absent or poorly developed in siltstones and shales within the overbank units due to differences in rock properties during the loading-unloading cycle (Voight & St. Pierre 1974; Engelder 1985).

Fracture identification: image logs

A cumulative total of 3,862 m of slimline acoustic scanner (SAS) image log data was acquired by BMA in 18 wells within the underground area to help predict underground mining conditions. The image logs have been used in this study for detailed analysis of natural fracture development and the effects of mechanical stratigraphy. Suites of wireline logs (sonic, density and gamma) were acquired in the wells with image logs and are used in this study to define the mechanical stratigraphy and link it to the image log interpretation (Fig. 5).

Natural fractures appear as either complete or partial sinusoids on an unwrapped image log and appear as low amplitude events (brown sinusoids) on the amplitude images (Fig. 10). Fractures that appear as distinct, complete or partial sinusoids are termed high confidence picks. Fractures that are not readily picked have more error associated with the interpretation and are termed low confidence picks. The confidence of the picks is a function of the image quality, which in turn is a function of the impedance contrast between fractures and host rock, fracture aperture and signal to noise ratios (Rider 2000). The remainder of this study discusses only high confidence fractures. Coal cleats are below SAS resolution and are not considered here. No attempt has been made in this study to distinguish fracture aperture because the ability of
Figure 11. Stereo and rose plot of all high confidence fractures showing dominant east-west and north-south striking trends.

Fracture interpretation: image logs

The type and origin of each fracture set must be known in order to facilitate successful fracture modelling. Fractures observed in outcrop may be identified as either tensile, shear or mixed mode based on surface ornamentation such as plume structures and slickenlines or by other relationships such as infilling or offset (Price & Cosgrove 1990; Davis & Reynolds 1996). These indicators are often not identifiable on image logs hence fractures identified on image logs must be classified in another manner. Observations made in the mine workings are used to help classify the fracture sets according to their dip angle and are in general accordance with basic Andersonian theory (Fig. 12). The orientation of the low, moderate and high-angle fractures interpreted from the image log data is consistent with the fracture orientations observed in outcrop and they are thus assumed to be of the same origin. Figure 13 shows combined rose and stereo plots for all fractures observed on the image logs separated according to dip angle.

The low-angle fractures (Fig. 13, left) have a dominant strike of north–south +/- 15º and are interpreted as small thrust faults and related damage zone fractures formed during the Early to Mid Triassic Hunter Bowen Orogeny. Several thrust faults are intersected by wells with image logs, including borehole 40993 (Fig. 14). The fault shown in Figure 14 is an east-dipping thrust fault with maximum throw in the order of 5 m and is resolvable in the seismic volume (Figs 3, 4). Borehole 40993 intersects the fault within an overbank unit 7 m below the Goonyella Middle Seam (GMS). The fault has a 0.5–1 m thick fault zone comprising a series of closely spaced low-angle fractures. A damage zone comprising a series of low-angle fractures, spaced in the order of 1 m, surrounds the fault zone similar to the fault exposed in outcrop (Fig. 7). The high-angle fractures (Fig. 13, centre) have a dominant strike of east–west +/- 5º generally have no offset and terminate at bedding planes defining mechanical units. The high-angle fractures are interpreted as uplift-related tensile joints.

The moderately dipping fractures (Fig. 13, right) have two dominant strike directions, north–south +/- 15º and east–west +/- 15º. Some of the moderate-angle fractures may be small normal faults associated with sediment compaction or accommodation structures associated with the thrusting. Some of the east–west striking set may be anomalously low-angle joints and some of the north–south striking set may be anomalously high-angle shear fractures associated with the thrust faulting.

The plots shown in Figure 13 show remarkably consistent orientations as summarised in Table 2. Table 2 shows the dominant orientations of low, moderate and high-angle fractures grouped according to the mechanical units and as a combined total. Figures 15 and 16 demonstrate the variation in low and high-angle fracture orientation between the wells. The figures demonstrate the variability in average fracture orientation between wells and the difficulty of accurately representing the fracture network away from the immediate well area.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Low</th>
<th>Moderate</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>15º</td>
<td>105º; 360º</td>
<td>95º</td>
</tr>
<tr>
<td>Overbank</td>
<td>360º</td>
<td>90º; 185º</td>
<td>90º</td>
</tr>
<tr>
<td>Channel</td>
<td>350º</td>
<td>145º; 85º</td>
<td>90º; 135º</td>
</tr>
<tr>
<td>Combined</td>
<td>360º</td>
<td>90º; 360º</td>
<td>90º</td>
</tr>
</tbody>
</table>
Figure 14. Acoustic image log of borehole 40993. Borehole 40993 intersects the GMS 7 m above a seismically resolvable thrust fault (Fig 4). Note the low angle fractures within the damage zone.

Figure 15. Low angle fracture orientation in each well. The orientations presented are for all high confidence low angle fractures. The number of high confidence fractures interpreted at each well is noted in brackets.

Figure 16. High angle fracture orientation in each well. The number of high confidence fractures in each well is noted in brackets.
Orientation and density are two of the most important characteristics of a fracture population. Variations within a fracture population may be due to sampling errors (Narr 1991) or spatial variations of either mechanical properties (Becker & Gross 1996; Odling et al. 1999; Underwood et al. 2003) or applied strain (Cooke et al. 2000; Hennings et al. 2000). Fractures must be considered with regard to their origin in order to assess the spatial variation in fracture density. The density of low, moderate and high-angle fractures varies between the different mechanical units and between wells. Fracture densities were weighted to account for the relative angle between the fracture plane and the borehole trajectory by dividing the raw fracture count by sinq, where q = angle between borehole trajectory and dip of fracture plane (Narr 1991). Table 3 and Figure 17 show the weighted and unweighted density of low, moderate and high-angle fractures in the different mechanical units. Low-angle fractures are significantly more frequent in the overbank facies than in either the coal or amalgamated channel units. High-angle fracture density is a function of unit thickness, being highest in the coal seams and lowest in the channel units.

Most of the high-angle fractures are interpreted as uplift-related and the primary controls on their distribution are lithology and thickness of the individual mechanical units. Variation of uplift-related joint density can be accounted for by spatial variations in the mechanical units sampled by the image logs. Thick distributary channel units with well developed but widely spaced joints have low fracture density which may appear even lower due to sampling errors given the low angle between joint dip and the boreholes. Overbank units comprising high shale and siltstone content and low sandstone content also display limited joint development. Overbank units with numerous thin sandstone bodies tend to have well developed, more closely spaced joints within the sandstone bodies and have high joint density.

Low-angle fractures have been shown in both outcrop and image log data to cluster around larger thrust faults (Figs 7, 14). The low-angle fracture density is related to deformation during the Hunter Bowen Orogeny and may be quantified by the proximity to thrust faults. Figure 18 is a map of low-angle fracture density from the image log data relative to seismically resolvable faults. The values are unweighted and are a combined total for the different units. The faults shown are near the bottom of the logged interval at the base of the GMS. If the faults were projected to the top of the logged interval they would be some 300–500 m further west so that at the middle of the logged interval, the largest fault would run approximately through the middle of the high-density zone.

Figure 18 shows that the density of low-angle fractures increases with proximity to the seismically resolvable thrust faults. Variance is least in the direction parallel to thrust fault strike and is greatest perpendicular to thrust fault strike. Such a result might have been anticipated, but its verification has major implications for reservoir exploitation in similar environments. The low-angle fractures associated with the thrust faults may impart significant permeability anisotropy and influence reservoir behaviour if the fractures are open and hydraulically conductive.

Low-angle fracture density at Goonyella Riverside is also a function of the mechanical stratigraphy. The effect of the mechanical stratigraphy may be analysed by comparing low-angle fracture density within overbank units in the sand-prone and coal-prone intervals (Table 4). The low-angle fracture density in overbank units within the sand-prone interval (0.16/m) is approximately 200% greater than in overbank units within the coal-prone interval (0.08/m). The difference between the two intervals can be explained in terms of mechanical stratigraphy, bedding plane slip and strain partitioning. The overbank units are the least

Table 3. Unweighted and weighted fracture densities for low, moderate and high angle fractures in the different units.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Low angle</th>
<th>Medium angle</th>
<th>High angle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unweighted</td>
<td>Weighted</td>
<td>Unweighted</td>
</tr>
<tr>
<td>Coal</td>
<td>0.04 /m</td>
<td>0.05 /m</td>
<td>0.12 /m</td>
</tr>
<tr>
<td>Overbank</td>
<td>0.14 /m</td>
<td>0.16 /m</td>
<td>0.23 /m</td>
</tr>
<tr>
<td>Channels</td>
<td>0.03 /m</td>
<td>0.04 /m</td>
<td>0.07 /m</td>
</tr>
<tr>
<td>Combined</td>
<td>0.09 /m</td>
<td>0.10 /m</td>
<td>0.17 /m</td>
</tr>
</tbody>
</table>

Table 4. Density of thrust-related low angle fractures (<45°) in the overbank units within the sand-prone and coal-prone intervals.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Cumulative thickness</th>
<th>Sum</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone-prone</td>
<td>1638.6 m</td>
<td>267</td>
<td>0.163/m</td>
</tr>
<tr>
<td>Coal-prone</td>
<td>786.2 m</td>
<td>61</td>
<td>0.078/m</td>
</tr>
</tbody>
</table>
Fracture development at Goonyella Riverside

Mechanical stratigraphy and the local tectonic history are the primary controls on fracture development at Goonyella Riverside. Three distinct stages of fracturing have been identified by this study.

I. Coal cleats and compaction-related normal faults formed during Late Permian burial and diagenesis. Coal type is the principal control on cleat development. Face cleat spacing in the bright vitrinite-rich layers is typically in the order of 5 mm and spacing in the dull inertinite-rich layers is more variable ranging from 20–150 mm. The face cleats generally strike east–west +/- 10° and the butt cleats are arranged in an orthogonal pattern about the face cleats typically striking north–south +/- 20°.

II. Thrust faults and subsidiary low-angle fractures formed during the Early to Mid Triassic Hunter Bowen Orogeny. The thrust faults strike near north–south and are subsidiary structures of the regional Jellinbah thrust system. The faults have maximum throw of approximately 5 m and display ramp-flat geometries detaching along the top of coal seams. The thrust faults have damage zones characterised by low-angle shear fractures spaced in the order of 0.5–1 m (Figs 7, 14).

Low-angle fracture density is greatest in the overbank units and increases with proximity to the thrust faults. Thrust fault-related low-angle fracture density increases with proximity to thrust faults. Variance is least in the direction parallel to fault strike and greatest perpendicular to fault strike (Fig. 18).

III. Tensile joints formed during the Cretaceous uplift and unloading. The joint sets are not expected to occur below a few hundred metres. The dominant joint set strikes east–west +/- 20° with a minor northwest–southeast striking set. Joint density is directly controlled by mechanical stratigraphy and is proportional to the thickness of each mechanical unit. Joints are most dense in coal seams and least dense in amalgamated channel units with spacing to height ratios in the range 0.7–1 (Fig. 9). Within the overbank units, joints are better developed in sandstone intervals than siltstone and shale intervals due to differences in rock properties during the loading-unloading cycle (Engelder 1985).

Discussion: implications for hydrocarbon development

The image log data used in this study is significantly more closely spaced than typical petroleum wells and demonstrates how ineffectively a single well with image log data may represent a fracture network away from the immediate well area. However, fracture networks can be accurately described from image log data if they are considered in the context of mechanical stratigraphy and local tectonic history.

Fracture systems at the surface may not reflect fracture systems at reservoir depth. Uplift-related joints are often the most prevalent features in outcrop yet they are unlikely to occur deeper than a few hundred metres (Davis & Reynolds 1996) and are probably absent from most hydrocarbon systems in on-shore Australia. Conversely, tectonically-induced fractures that occur at reservoir depths will not exist at outcrop levels if the fractures are older than the outcropping rocks. This scenario occurs in the Surat-Bowen basins where uplift-related fractures observed in outcrop of the Surat Basin do not occur at reservoir depth in the underlying Bowen Basin and tectonically-induced fractures present in Bowen Basin reservoirs are not present in the outcropping, overlying Surat Basin (Flottmann et al. 2002). When modelling a fracture system it is critical to identify which groups of fractures may occur at reservoir level. Of the fractures identified at Goonyella Riverside, coal cleats, thrust faults and associated damage zones, and normal faults are expected to occur at typical reservoir depths in similar settings.

Coal cleat development influences both reservoir permeability and well completions/stimulations and is a primary control on the economic viability of coal seam methane projects (Gray 1987; Johnson et al. 2002; Zuber & Boyer 2002). Coal type appears to be the most significant influence on cleat development. Vitrinite-rich layers typically have more closely spaced cleats providing increased coal permeability and may improve the success of cavitation completions. However, it is difficult to model discrete coal cleats from image log data because diagenetic coal cleats are below image log resolution. An alternative method for coal cleat modelling may be the prediction of coal type using sequence stratigraphic approaches to predict vitrinite-rich intervals (Bocking pers. comm. Bocking Associates CBM 2003).
Fault-related fractures similar to those at Goonyella Riverside may provide high permeability streaks within otherwise tight reservoirs. The fractures are un-mineralised and hydraulically conductive within the in-situ stress field. In fact, the thrust fault and damage zone intersected by borehole 40993 (Figs 3, 14) accounted for almost half the ground water entering the Goonyella Riverside underground exploration adit (Callow & Briese 2002). Natural fractures are exploited in many mature fields with low matrix permeability including fields within the San Juan, Appalachian and Piceance basins of the USA. Fault-related fractures similar to those observed at Goonyella Riverside (Figs 7, 14) are exploited in dolomites of the Trento-Black River play in the Appalachian Basin (Laubach 2003). The fault zones frequently have low permeability and act as flow baffles, but fractures within damage zones beyond the fault zone significantly enhance permeability and contribute substantially to reservoir performance (Laubach 2003). In the San Juan Basin, continued gas production from tight, lenticular sandstone reservoirs (0.01–60 mD) of the Mesaverde and Dakota formations is fracture dependent (Teufel 2003; Teufel & Herrin 2003). Well tests indicate horizontal permeability anisotropy of approximately 10:1 within the fractured Mesaverde reservoirs (Teufel & Herrin 2003). Fault-related fracture swarms similar to those exploited in the USA could be targeted for high-rate wells in existing Australian on-shore fields by targeting seismically resolvable fault zones as observed at Goonyella Riverside (Figs 3, 4, 14). Any offset/infill wells should ideally avoid previously tapped fracture swarms to avoid drainage interference and should be based on appropriate elliptical drainage patterns (Bell & Babcock 1986; Hart et al. 2002; Teufel & Herrin 2003). Even with significant fault-related fracture permeability, hydraulic fracture completions may be required to connect the fractured intervals for commercial production (Cumella et al. 2002). However, difficulties may arise with hydraulic fracture completions near faults due to fault-related stress perturbations and the typically high-stress environment of onshore Australia (Bell & Babcock 1986; Bell 1996; Hillis et al. 1998; Yule 2003).

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