A SYSTEMATIC FAULT SEAL EVALUATION OF THE
LADBROKE GROVE AND PYRUS TRAPS OF THE
PENOLA TROUGH, OTWAY BASIN

P.J. Lyon¹, P.J. Boult¹,², M. Watson¹ and
R.R. Hillis¹
¹Australian School of Petroleum
University of Adelaide
Adelaide SA 5005
²Department of Primary Industries and Resources
Petroleum Group
Level 7
101 Grenfell St
Adelaide SA 5001
plyon@asp.adelaide.edu.au
boult.peter@saugov.sa.gov.au
mwatson@asp.adelaide.edu.au
rhillis@asp.adelaide.edu.au

ABSTRACT

Juxtaposition mapping of lithology onto the Ladbrooke Grove Fault plane shows that the Pretty Hill Sandstone reservoir, which hosts a 90 m gas column, juxtaposes massive shale units in the hangingwall. Retention of the column at Ladbrooke Grove can thus be attributed to favourable across-fault, reservoir-seal juxtaposition. The free water level (FWL) of the Ladbrooke Grove column coincides with an abrupt change in strike of the fault from east–west to northwest–southeast. Fault re-activation risk using the FAST (Fault Analysis Seals Technology) technique indicates that the northwest–southeast striking segment of the fault is critically oriented within the in-situ stress field for re-activation, whereas the more east–west trending segment is associated with a relatively lower risk of fault re-activation. Hence recent slip along the northwest–southeast segment may have created permeable fracture networks along this part of the fault plane and thus limited the extent of the column to that bounded by the east–west trending fault segment. This hypothesis is supported by data on soil gases acquired across the fault which suggest that the fault is leaking CO₂ across its northwest–southeast striking segment, but not across its east–west striking segment.

The Pyrus Fault is not presently sealing by across-fault, reservoir-seal juxtaposition. The throw on the fault plane is sufficient to juxtapose the Katnook Sandstone in the hangingwall against the Pretty Hill Sandstone reservoir in the footwall, providing a sand-on-sand juxtaposition leak point at the structural apex of the trap. Fault re-activation along this fault is likely to have caused fracturing of any shale gouge veneer that may have been present along this sand-on-sand contact resulting in across-fault leakage of hydrocarbons into the Katnook Sandstone and leakage up the fault along permeable fracture networks. FAST predictions of fault re-activation show that the fault is critically oriented within the in-situ stress field for re-activation and soil gas measurements at the surface suggest the fault is leaking CO₂.

KEYWORDS

Fault seal, juxtaposition, shale gouge, re-activation, leakage.

INTRODUCTION

Exploration interest in fault-dependent traps within the Pretty Hill Sandstone reservoir of the Penola Trough, Otway Basin has waned recently due to the frequent encountering of palaeo-hydrocarbon columns, i.e. columns that were once present, but have since leaked due to seal breach. These palaeocolumns occur within the same play type as five commercially-producing gas fields (Fig. 1), thus making the Penola Trough an ideal location for testing seal analysis predictions.

The Laira Formation forms the overlying regional seal to the Pretty Hill Sandstone reservoir (Fig. 2). It is laterally continuous and consists of frequent, fine shale units with excellent seal capacity, capable of holding back columns far beyond the structural spill point of the traps (Boult, 1997). For these reasons, top seal risk in the area is considered minimal, and hence fault-related seal breach has been considered the key risk to seal integrity (Hillis et al, 1995; Jones et al, 2000; Willink and Lovibond, 2001; Boult et al, 2002a).

Jones et al (2000) identified recent fault re-activation as the possible cause of fault seal breach in the Penola Trough and assessed the probability of fault re-activation with FAST (Fault Analysis Seals Technology). FAST is a technique that quantifies the relative risk of fault re-activation in terms of in-situ stress and rock properties (Mildren et al, 2002; Mildren et al, in press). Although FAST predictions of fault re-activation have been successfully calibrated to the present day distribution of hydrocarbon columns in the Timor Sea (Mildren et al, 2002), FAST predictions of fault re-activation did not fully explain the distribution of hydrocarbon columns in the Penola Trough (Boult et al, 2002a). This suggested that mechanisms other than recent fault re-activation may be significant to hydrocarbon leakage.

Boult et al (2002a) proposed a mechanism of breach by fracturing of intact top seal due to stress perturbations that occur locally around faults. Areas of high differential stress and thus high risk of cap seal breach have been predicted through stress modelling (Camac et al, 2004; Hunt and Boult, in press). Although there is a good correlation between predictions of high differential stress and the distribution of palaeo-columns, an anomalous area remained where low differential stress corresponded with
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The location of live and breached columns in the Penola Trough, Otway Basin displayed on a near top Pretty Hill Formation horizon interpretation (from Origin Energy). The location of the Ladbroke Grove and Pyrus traps on the flanks of the Katnook Graben are also indicated.

the interpreted presence of a palaeocolumn hosted by the Pyrus structure (Fig. 1 for location).

The breaching of the Pyrus structure has frequently proved to be enigmatic to stress-based methods of seal integrity analysis in the Penola Trough (Boult et al, 2002a; Boult et al, 2004). It hosts only residual hydrocarbons, despite its apparent structural similarity and proximity to the oppositely dipping Ladbroke Grove Fault (Figs 1 and 3) which holds a commercial gas column.

We believe that there are two key reasons why the stress-based methodologies have not been completely successful in the Penola Trough. Firstly, fault geometries have not always been carefully determined in depth (Boult et al, 2004). Secondly, stress-based methods have not always been fully integrated with across-fault juxtaposition and fault damage (e.g. shale gouge) aspects of fault seal risk (Jones and Hillis, 2003; Lyon et al, in press). The latter is of particular importance to understanding the live and breached status of the Ladbroke Grove and Pyrus traps respectively.

In this paper, we reassess the fault seal integrity of Pyrus and Ladbroke Grove traps in a systematic assessment of structural geometry, juxtaposition, fault damage and fault re-activation potential. The structure of the Pyrus and Ladbroke Grove traps is re-interpreted using a new seismic interpretation methodology that uses depth-based seismic sections in addition to time based sections (Lyon et al, 2004). Shale volume estimates determined from well log data are tied to seismic horizon data and projected onto the fault plane surfaces in the modelling of across-fault juxtaposition (Downey, 1984; Jev et al, 1993) to assess whether sand-on-sand juxtaposition ‘leak windows’ are present across the faults. The shale gouge ratio algorithm (SGR; Yielding et al, 1997) is used to determine the seal potential of fault damage processes, namely the incorporation of shale gouge into the fault zone by mechanical processes during fault movement. An assessment of the risk of fault re-activation in the in-situ stress tensor using 3D FAST analysis (Mildren et al, in press) is undertaken. These FAST results are compared to newly-acquired carbon dioxide leakage data measured at the surface as well as the 3D extent of the observed live column and palaeocolumn of the Ladbroke Grove and Pyrus traps respectively.

REGIONAL GEOLOGY

The Otway Basin formed as a result of rifting and continental break-up of Australia and Antarctica. Rifting was
initiated along the presently onshore part of the basin in the Late Jurassic (Lovibond et al, 1993; Fig. 2). The Penola Trough is one of a series of onshore half-graben structures that formed as a result of initial rifting during this time (Perincek et al, 1994). It is a northwest–southeast trending structure and is bound to the southwest by a large northeast dipping listric fault complex known as the Hungerford/Kalangadoo fault system (Fig. 1; Finlayson et al, 1993).

Initial sedimentation in the Penola Trough was dominated by lacustrine sediments of the Casterton Formation (Morton, 1990). This was followed by the deposition of the Crayfish Group, which includes the Pretty Hill Formation, the overlying Laira Formation and Katnook Sandstone Member. The Pretty Hill Formation has been subdivided into several members, namely:

- the Lower Sawpit Shale Member;
- the Sawpit Sandstone Member;
- the Upper Sawpit Shale Member; and
- the Pretty Hill Sandstone Member (the main target reservoir) at the top of the sequence (Boult et al, 2002b; Fig. 2).

The Pretty Hill Sandstone reservoir consists of massive, slumped and cross-bedded sand packages deposited in a braided fluvial environment and has been classified lithologically as a litharenite to feldspathic litharenite (Alexander, 1992; Little, 1996). The Laira Formation top seal, which comprises interbedded siltstones, shales and occasional sands was deposited in an overbank to lacustrine environment (Kopsen and Scholefield, 1990). The Katnook Sandstone, at the top of the Crayfish Group sequence, is locally preserved within downthrown fault blocks such as the main gas-bearing Katnook Graben structure.

The Casterton Formation and Crayfish Group show syn-sedimentary growth into intra-rift faults formed during the initial rifting phase in the Early Cretaceous. These intra-rift faults strike east–west in the central part of the Penola Trough, but at the margins of the Trough their strike is predominantly northwest–southeast (Fig. 1).

Cessation of initial rifting within the Penola Trough was coincident with a period of erosion on uplifted footwall escarpments marked by the unconformity surface at the top of the Crayfish Group. Only minor fault movement occurred throughout the Aptian-Albian deposition of the Eumeralla Formation in the Penola Trough and surrounding onshore depocentres as the initial rifting shifted to the more distal offshore parts of the Otway Basin (Palmowski et al, 2004). The Eumeralla Formation was deposited in a fluvio-lacustrine environment and consists of interbedded volcanogenic lithic sandstones, siltstones, coals and claystones (Cockshell et al, 1995). Sediments of the overlying Sherbrook Group were deposited in the Late Cretaceous under fluvio-deltaic conditions and consist of frequent mudstone and massive sandstone units (Morton et al, 1995). The Tertiary succession can be sub-divided into the Wangeripp, Nirranda and Heytesbury Groups and generally shows a transition to a dominantly marine environment of deposition with frequent occurrences of massive limestone sequences.

A significant faulting episode commenced in the Late Cretaceous (Lyon et al, 2004). This resulted in the development of new faults, showing a more consistent northwest–southeast orientation than the initial rift faults of the Early Cretaceous. Re-activation of large east–west Early Cretaceous faults, such as the Ladbrooke Grove Fault and Pyrus Faults occurred concurrently (Lyon et al, 2004). A phase of northwest–southeast compression began in the Miocene and is evident from hangingwall inversion of several of the major faults of the area including the Ladbrooke Grove fault in particular (Rowe, 1996). Several faults in the area show displacement to the surface indicating that fault activity has continued through to the present day.
Hydrocarbon charge in the Penola Trough was substantial, particularly into the Katnook Graben area (Fig. 1) where both the Katnook and Redman fields are full to structural spill point. The Katnook and Redman Fields are both likely to have spilled gas into the Ladbroke Grove and Pyrus structures on the upthrown flanks of the graben (Boult et al, 2004). Thermal maturity modelling suggests that hydrocarbon generation peaked around the Mid Cretaceous, contemporaneous with the deposition of the Eumeralla Formation (Lovibond et al, 1995; Duddy, 1997), comprising an early oil charge followed by a later gas charge (Boult et al, 2004). The presence of many structural traps that are full to spill with gas in the present day indicates that a later gas charge phase must have occurred recently (i.e. within at least the last 10–20 Ma) to counterbalance rates of gas loss by diffusion (Nelson and Simmons, 1995, 1997; Krooss and Leythaeuser, 1997).

Recent charge by CO$_2$, likely to be of magmatic origin related to recent volcanic activity (Chivas et al, 1987), is evident in the Penola Trough and represents a key risk to gas exploration (Willink and Lovibond, 2001). High concentrations of CO$_2$ are associated with structural traps bound by large scale faults such as the Hungerford Fault and Ladbroke Grove Fault (Fig. 1). Geochemical analysis of the Ladbroke Grove Field shows that there is an increasing gradient of CO$_2$ from the base of the column (56 mol%) to the top of the trap (29 mol%) (Simeone and Mitchell, 2001). It is therefore likely that CO$_2$ charge is still occurring in the present day (Boult et al, 2004).

**TRAP GEOMETRY**

The structure of the Katnook Graben was interpreted using both time-based and depth-based 3D seismic data from the Balnaves-Haselgrove reprocessed survey (Fig. 3). The method used to depth convert the seismic data is described in Lyon et al (2004). Variance slices were derived from both seismic datasets to facilitate the picking of faults and quality control of interpretation. Further quality control of fault interpretation was undertaken using 3D visualisation software (Fig. 4). Several key horizons were interpreted including the top Sherbrook Group, top Eumeralla Formation, the top Crayfish Group and a near top Pretty Hill Formation horizon (Fig. 3). The interpreted top Sherbrook Group, top Eumeralla Formation and top Crayfish Group unconformity horizons tie closely with the formation top picks in all wells. There were slight
Figure 4. 3D structural depth model of the Katnook Graben showing the Ladbroke Grove and Pyrus traps (top) and the 3D extent of the live column and interpreted palaeocolumn displayed on the top Pretty Hill Sandstone reservoir horizon (bottom). Contour spacing is 75 m (1:1 depth scale).
discrepancies between the depth of formation tops and the seismic horizons of up to 20 m in the case of the top Crayfish Group; however, these errors are found to be within the range of vertical seismic resolution at a depth of 2–3 km. It was not possible to confidently pick the actual top of the Pretty Hill Sandstone reservoir as it is rarely distinguishable as a distinct seismic reflector. Due to the abundant well data in the area, however, it was possible to produce a top Pretty Hill Sandstone reservoir horizon on completion of the interpretation by the generation of a duplicate horizon surface above the near-top Pretty Hill Formation horizon that was consistent with the depths of formation top picks in of all the wells in the area (Ladbroke Grove–1, –2, –3, Katnook–1, –2, –3, –4, Redman–1, Pyrus–1, Wynn–1).

The Pyrus and Ladbroke Grove Faults show displacement from >6 km depth to the surface. They are relatively large faults that are likely to have been re-activated continually throughout the structural evolution of the area (Lyon et al, 2004).

The Pyrus Fault offsets basement and is relatively planar in geometry, with a consistent east–west strike along its length (Figs 3 and 4). The Pyrus–1 well was drilled slightly offset to the structural apex of the trap and intersected the interpreted palaeocolumn within the the top two sands of the Pretty Hill Sandstone (Boult, 1997). A palaeo free-water level (PFWL) is interpreted to occur at 43–65 m beneath the top of the Pretty Hill Sandstone in the well (Boult, 1997).

The Ladbroke Grove Fault is linked to the Pyrus Fault at depth and is interpreted to have formed as a consequence of footwall collapse caused by displacement on the Pyrus Fault. It shows a similar size and geometry to the Pyrus Fault, but from east to west a significant strike variation to a more northwest–southeast direction is shown (Figs 1 and 4). A more planar geometry than the Pyrus Fault, is shown along its east–west part, with a more sub-planar geometry along its northwest–southeast trending part. Interestingly, the gas column at Ladbroke Grove is bound only by the east–west trending part of the fault. The FWL, interpreted from RFT data, occurs at a depth of 2,502 mSS and closely coincides with the point where the fault strike changes to a more northwest–southeast orientation (Fig. 4).

**SHALE VOLUME**

Prediction of fault seal characteristics in terms of juxtaposition and shale gouge ratio requires accurate determination of the shale volume in the stratigraphic sequence from log data. Shale volume (Vshale) can be estimated from the gamma ray log (GR) by determining the maximum average gamma ray value, assumed to be 100% shale (shale line), and the minimum average gamma ray value, assumed to be 0% shale (sand line). All GR values are then assigned a Vshale, expressed as a percentage, by assuming a linear or non-linear relationship of increasing Vshale with increasing GR (Rider, 2000).

Histogram plots of the GR log permitted the precise picking of sand and shale lines and allowed the identification of outlier values that were omitted from the Vshale determination (Fig. 5). Previous work on Vshale determination has shown that for consolidated rocks the relationship of the GR log to the actual shale volume of the rock is best described by a non-linear relationship (Dresser Atlas, 1982; Rider, 2000). The following non-linear function from Dresser Atlas (1982) was thus used to derive a Vshale curve for seven representative wells in the area using the GR log (Katnook–1, –2, –4; Ladbroke Grove–1, –2; Redman–1 and Pyrus–1):

\[ V_{\text{shale}} = 0.33 \left( 2^{\frac{GR_{\text{log}}}{2}} - 1 \right), \]  

where Gamma Ray Index (GRI) =

\[ \frac{\text{GR(log value)} - \text{GR (min)}}{\text{GR(max)} - \text{GR (min)}}. \]

GR (min) is the minimum average GR value (sand line), GR (max) is the maximum average gamma ray value (shale line) and GR (log) is the gamma ray log value.

The Vshale derived from the GR log using the above equation was cross-checked with other shale indicator logs such as the Th log and D-N log to confirm that the GR log was a reliable indicator of shale volume for these rock types. This is described in more detail in Lyon et al (in press).

**STRATIGRAPHIC CORRELATION**

Intra-formational stratigraphy interpreted from well data is tied to surfaces interpreted from seismic and projected onto fault planes in the analysis of juxtaposition. The stratigraphy interpreted within the wells may not necessarily be representative of that adjacent to the
fault plane. It is therefore important to assess the likely continuity of units across the wells through stratigraphic correlation.

The Vshale curves for each well were used to subdivide the Laira Formation top seal into intraformational stratigraphic units. The presence and lateral continuity of sands was assessed in a stratigraphic correlation of each unit across the seven representative wells of the study area (Fig. 6). Intra-formational picks were made principally by the identification of laterally continuous shale peaks and observation of the coarsening relationships both vertically and laterally. The absence of a 270 m section of the Laira Formation due to fault displacement was identified in Ladbroke Grove–2 and was accounted for in the stratigraphic correlation (Fig. 6).

The interpreted basal units 5 and 6 of the Laira Formation show average Vshale values of about 40% with frequent sand lenses of up to 5 m thickness. Based on a typical width to thickness ratio of 1:100 for small isolated channel sands (Payen and Lang, 2003) these would be expected to have a maximum extent of up to 500 m. This is consistent with the observation that none of these sands can be correlated between wells. More regional stratigraphic correlation across the entire Penola Trough by Lovibond et al (1993) has also indicated that the generally more abundant sands within the Laira Formation occur in the basal units.

Units 3 and 4 of the Laira Formation are associated with an average Vshale of 40% and 43% respectively. These units show much less frequent and thinner sand lenses than Units 5 and 6, particularly in the Katnook and Redman wells. A notable anomalous sand of 9 m thickness in Redman–1 is recognised at the base of Unit 3. However, this sand appears to correlate with more shale prone units in the Katnook wells. Apart from this thin sand, there is a notable absence of sand lenses in Units 3 and 4.

Unit 2 shows very distinct and laterally continuous shale-rich layers with an average Vshale of 50–60%. These are likely to represent significant flooding events within this lacustrine palaeoenvironment setting. There are no significant sand lenses found within this unit or in the overlying Unit 1. Units 1 and 2 are notably absent in the Pyrus–1 well but display significant erosion of the upthrown Pyrus footwall in the Barremian, marked by the Crayfish unconformity. Erosion on the footwall of the Ladbroke Grove Fault also indicates this. The overlying Katnook Sandstone consists predominantly of sandstone units of a typical Vshale of 5% with frequent thin interbeds of shale rich units. Palynological analysis shows the Katnook Sandstone to consist of reworked Laira Formation indicating the existence of an additional erosional surface to the Crayfish unconformity between the top of the Laira Formation and the base of the Katnook Sandstone (Boult, 1997).

JUXTAPOSITION AND SHALE GOUGE RATIO

The intra-formational picks identified in the stratigraphic correlation were used to generate intra-formational surfaces that were isopached proportionally between the interpreted top Crayfish unconformity and near top Pretty Hill Formation seismic horizons. The seismic horizons and intra-formational surfaces were projected onto the interpreted Pyrus and Ladbroke Grove fault planes to create fault juxtaposition diagrams.

The juxtaposition analysis for the Pyrus Fault shows that the substantial throw on the fault plane, in excess of 1 km, is sufficient to completely displace the Laira Formation past the top of the Pretty Hill Sandstone of the Pyrus footwall trap (Fig. 7a). Hence the Katnook Sandstone is juxtaposed against the Pretty Hill Sandstone reservoir at the apex of the structure. This represents a potential sand-on-sand leaky window across the fault plane. The juxtaposition analysis for the Ladbroke Grove footwall trap (Fig. 7b) shows that the presently live column down to the FWL in the Pretty Hill Sandstone of the footwall is juxtaposed against Units 3 and 4 of the Laira Formation in the hangingwall. The more sand prone beds of Units 5 and 6 juxtapose the Pretty Hill Sandstone over 200 m below the FWL.

Shale gouge ratio was computed over the area on the fault plane where the Katnook Sandstone juxtaposes the Pretty Hill Sandstone on the Pyrus Fault (Yielding et al, 1997). The hangingwall Vshale from Redman–1 was used in the calculation of shale gouge ratio because of the lack of a complete Laira Formation section in Pyrus–1 due to erosion. A shale gouge ratio computation was not required for the Ladbroke Grove Fault as no potential sand-on-sand windows were identified above the FWL of the Ladbroke Grove accumulation.

The mean shale gouge ratio computed over the Katnook Sandstone/Pretty Hill Sandstone juxtaposition contact of the Pyrus fault was 43%.

FAULT RE-ACTIVATION

Post-charge re-activation of faults has often been associated with the breach of fault traps (Castillo et al, 2000; Jones et al, 2000; Mildren et al, 2002). The re-activation potential of the Ladbroke Grove and the Pyrus Faults was assessed using the FAST technique (Mildren et al, 2002). A brief overview of the technique is given here, but for a more detailed discussion the reader is referred to Mildren et al (2002) and Mildren et al (in press). FAST provides an assessment of the likelihood of a fault to re-activate within the in-situ stress field. The re-activation potential is quantified in terms of the increase in pore pressure (∆P) required for the resolved shear and effective normal stress acting on a fault plane of a given dip and strike to exceed a specified failure envelope. A low ∆P corresponds to a relatively high risk of fault re-activation and a high ∆P corresponds to a relatively low risk of fault re-activation. Three inputs are required for FAST analysis: the in-situ stress field, the fault rock failure envelope and fault orientation.

The following stress gradients in the Penola Trough were used to define the in-situ stress field used in the FAST analysis herein:
**Figure 6.** Stratigraphic correlation of formation tops and intra-formational units of the Laira Formation based on Vshale logs from seven representative wells of the study area.
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Figure 7. Juxtaposition diagram for a. the Pyrus Fault b. the Ladbroke Grove Fault showing the intraformational units in the hangingwall that juxtapose the displaced Pretty Hill Sandstone reservoir in the footwall.
• minimum horizontal stress ($S_{h_{\text{min}}}$) = 15.5 MPa/km;
• vertical stress ($S_v$) = 21 MPa/km;
• maximum horizontal stress ($S_{H_{\text{max}}}$) = 28.7 MPa/km;
• pore pressure ($P_p$) = 9.8 MPa/km; and
• maximum horizontal stress ($S_{h_{\text{max}}}$) orientation = 128°N.

The minimum horizontal stress was determined from six leak-off tests and two high quality extended leak-off tests (Fig. 8a). The vertical stress was calculated for five wells by integration of the density log using the methodology described by Tingay et al (2003). The maximum horizontal stress was constrained by the occurrence of drilling induced tensile fractures (DITF) in two wells using the methodology described by Brudy and Zoback (1999). The pore pressure gradient was determined from, high quality formation pressure tests and drill stem tests (Fig. 8a). The $S_{h_{\text{max}}}$ direction was constrained by the occurrence of 373 borehole breakouts of A-C quality (Zoback, 1992) interpreted from image logs in eight wells in the Penola Trough (Fig. 8b).

The failure envelope used was that determined from tri-axial testing of a core sample through a cataclastic fault zone in the Pretty Hill Formation in the Banyula–1 well (Dewhurst and Jones, 2002):

$$\sigma_s = 5.40 + 0.78\sigma_n',$$  \hspace{1cm} (2)

where:
$\sigma_s$ is shear stress at failure and $\sigma_n'$ = effective normal stress (i.e. on $-P$) with all pressure units in MPa.

The above criteria were used to assign a re-activation risk ($\Delta P$) to the 3D fault surface of Ladbroke Grove and Pyrus Faults. Figure 9 shows the $\Delta P$ value plotted on the part of the fault plane where the Pretty Hill Sandstone reservoir has been displaced, i.e. the part of the fault crucial to fault seal integrity. The Pyrus fault shows the highest risk of fault re-activation with an average $\Delta P$ of 16 MPa along its length. The northwest–southeast trending part of the Ladbroke Grove Fault shows a similarly high risk of re-activation with an average $\Delta P$ of 17 MPa. However, the east–west component of the Ladbroke Grove Fault shows a much lower risk of re-activation with an average $\Delta P$ of 23 MPa.

**CARBON DIOXIDE SOIL GAS ANALYSIS**

Carbon dioxide (CO$_2$) soil gas data has been acquired over the study area to investigate leakage patterns of CO$_2$. Three CO$_2$ soil gas sampling transects were run across the Ladbroke Grove and Pyrus faults to test for increased levels of CO$_2$ at the surface (Fig. 10). Sample spacing was 100 m along lines running normal to the faults. The spacing of soil gas samples decreased to 50 m when crossing the extrapolated near surface position of the fault, based on seismic interpretation. At each sample point a 4 cm hole was manually augered to ~1 m depth, ensuring that the organic rich soil horizon was passed. The soil gas was sampled in-situ, using a Vaisala GMT221 carbon dioxide transmitter with a 0.01 to 10% CO$_2$ detection range and...
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Figure 9. 3D depth model showing the FAST attribute ($\Delta P$) computed on the part of the Ladbroke Grove and Pyrus faults where the top Pretty Hill Sandstone horizon has been displaced. The Pyrus Fault and the NW–SE trending part of the Ladbroke Grove Fault are associated with a relatively high risk of fault reactivation (red). The E–W trending part of the Ladbroke Grove Fault is associated with a relatively low risk of fault reactivation (blue/green).

LIMITATIONS

This section discusses some of the limitations of the fault seal analysis presented herein.

Fault geometry interpretation

The excellent seismic imaging of the Ladbroke Grove and Pyrus Faults has allowed accurate interpretation of their geometry. Interpretation of fault segments were consistent when viewed using 3D visualisation software allowing confident modelling of the fault segments into fault planes, particularly over the area of structural closure of the traps. The data quality does, however, slightly decrease away from the structural apices of the traps towards the tips of the faults. The interpreted faults are, however, limited by the resolution of the seismic data. Previous studies have shown that sub-seismic relay zones

a precision of 0.02% of total soil gas. CO$_2$ soil gas levels were recorded one minute after stabilisation of the reading. Soil type, atmospheric pressure, temperature and other environmental factors were included in the recording. Background CO$_2$ soil gas measurements were also taken at locations removed from any natural CO$_2$ accumulations in a similar soil type to the study area.

Transect 1 over the northwest–southeast part of the Ladbroke Grove fault, predicted to have a relatively high risk of re-activation, coincides with a strong CO$_2$ anomaly of 0.8% (Fig. 10). Transect 2 over east–west trending part of the fault, which has a relatively low risk of re-activation, is not associated with a significant CO$_2$ anomaly at the surface. A CO$_2$ anomaly of 0.55% was also found to coincide with the position of the Pyrus fault in transect 3.
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are a key risk to prospect integrity and these were not accounted for in this analysis (Childs et al, 1996; Childs et al, 1997).

Occurrence of Palaeocolumns

The interpretation of the existence of a palaeocolumn at Pyrus is considered by Boult et al (2004) to be the most speculative of all the palaeocolumns in the Penola Trough. It was originally interpreted on the basis of significant gas shows within the top two sands of the Pretty Hill Sandstone, as well as from analysis of total gas plotted against drilling rate of penetration (Boult, 1997). Recently GOI (grain oil inclusion) analysis by Lisk (2004) has indicated that Pyrus exhibits a higher percentage of grains with oil inclusions than may be expected for a typical migration pathway in this area. The existence of a column at Pyrus, however, remains somewhat speculative.

Juxtaposition and SGR analysis

The mismatch of up to a maximum of 20 m observed between the top Crayfish seismic reflector and the top Crayfish Group in the wells presents a potential error in the juxtaposition and SGR analysis. Furthermore the geometry of the top Pretty Hill Sandstone reservoir horizon may not necessarily exactly reflect that of the near top Pretty Hill reflector from which it was created.

The degree to which lithologies vary laterally along the fault plane and away from well control also limits the analysis of juxtaposition and SGR (Bretan et al, 2003). An assessment was made of potential lateral Vshale variation of each unit along the Ladbroke Grove Fault plane using a simple, fit for purpose stochastic model (e.g. James et al, 2004). The method used is summarised below.

- Each intra-formational unit of the completed 3D structural model was sub-divided into discrete layers with an average thickness of 40 m.
- The Vshale log was averaged over each discrete layer for each well. These values were then used in the stochastic population of a 3D cellular grid with Vshale values using a sequential Gaussian simulation (Fig. 11). An exponential variogram with an east–west orientation bias of 2 km x 1 km (consistent with the likely palaeo-flow direction and the estimated lateral extent of the layers between the wells) was used in the modelling. Five iterations were performed to ensure that the observed distribution was repeatable. The results for

Figure 10. The location and results of CO₂ soil-gas transects acquired over the interpreted surface location of the Ladbroke Grove and Pyrus Faults.
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each layer were also cross-checked with the well logs to ensure that the upscaled cells were representative and consistent with the observed trends.

- Vshale values for the cells adjacent to the fault plane in the hangingwall of the Ladbroke Grove Fault (Fig. 12) were analysed to observe the modelled Vshale variation across the fault plane.

The average Vshale variation along the hangingwall of the fault for each unit was typically between 5–12% over several iterations of the simulation and the Katnook Sandstone exhibited the greatest variability. This was found to impact the prediction of SGR by ±5%. Furthermore, there was an overall low risk of juxtaposition of intra-formational sand lenses in the Laira Formation against the live column in the footwall of the Ladbroke Grove Fault.

More work is required to improve this kind of modelling. One clear problem is that in seal evaluation the continuity of even thin discontinuous sands of only several metres thickness can be significant to juxtaposition. It is difficult to accurately upscale such heterogeneity into a reliable model. The magnitude of Vshale variation due to stratigraphic uncertainty estimated from this modelling does not, however, affect the overall interpretation of the juxtaposition and SGR results detailed in the discussion.

Risk of re-activation and leakage.

The in-situ stress tensor used is the FAST analysis is considered reliable and was constrained by a large dataset compiled from 15 wells in the area. The greatest likely errors lie in the use of core-scale testing to assign a prospect scale failure envelope to the faults. Variation of the failure envelope would significantly affect ΔP values, but would have little effect on relative risk of failure of differently oriented fault segments ( Mildren et al, in press). The CO2 leakage data is limited to only three transects over these faults and a more extensive collection of leakage data is required to be certain of the observed anomalies.

DISCUSSION

The Pyrus and Ladbroke Grove traps formed in the Early Cretaceous, as indicated by the syn-sedimentary character of the Early Cretaceous Crayfish Group (Fig. 3). Initial syn-sedimentary fault movement on these faults would have resulted in the smearing of shale from the country rock into the fault zone as the Laira Formation was progressively displaced past the Pretty Hill Sandstone under ductile conditions of rock deformation (Fisher et al, 2003). Thermal maturity modelling (Lovibond et al, 1995; Duddy, 1997) has shown that main charge phase in the Penola Trough occurred in the Mid Cretaceous, during deposition of the Eumeralla Formation. Hence, both the Pyrus and Ladbroke Grove structures were in place prior to the main phase of hydrocarbon charge.

Pyrus

The juxtaposition results for the Pyrus Fault indicate that its throw is sufficient to juxtapose the Pretty Hill Sandstone reservoir in the footwall against the Katnook Sandstone member in the hangingwall at the structural apex of the trap (Fig. 7a). Because the reservoir has been completely displaced past the entire Laira Formation seal, however, a high mean SGR of 43% resulted from the SGR calculation along this sand-on-sand window. Previous calibration of SGR values to maximum buoyancy pressures for a worldwide dataset by Bretan et al (2003) suggests that an SGR of 43% at a depth of 2,000 m would be capable of...
holding back buoyancy pressures of about 1 MPa which is equivalent to a gas column height of 100 m. Despite there being a high mean SGR value of 43% across this sand-on-sand juxtaposition leak window, however, the Pyrus structure hosts only residual hydrocarbons.

Structural interpretation of the Pyrus fault shows that it has been re-activated continually since its initiation in the Early Cretaceous. We therefore suggest that re-activation of this fault surface that occurred after the onset of juxtaposition of the Katnook Sandstone against the Pretty Hill Formation under brittle conditions of rock deformation (Fisher et al, 2003) was sufficient to cause brittle fracturing through any intact shale veneer that may have been present over this sand-on-sand contact. This would have caused the original column hosted by the prospect to leak across the fault into the Katnook Sandstone and also up the fault along permeable fracture networks. Across fault leakage at this sand-on-sand leak point is supported by observations of significant hydrocarbons shows within the Katnook Sandstone and interconnected basal Eumeralla Formation sands of the Katnook Graben (Reeve, 1995). It is likely that a post-charge re-activation across this sand-on-sand contact resulted in a permanent loss of seal integrity evident in the present day by the absence of a live column. Even though the fractures generated by fault re-activation slip across this contact may have re-healed between successive re-activation events, it is interpreted that this sand-on-sand contact is likely to have continued to serve as a leakage window across the fault to the present day.

The timing of this post charge juxtaposition seal breach is difficult to constrain but may not have been as recent as the re-activation of Zema where the evidence of a palaeo-column is more convincing (Boult et al, 2004; Lyon et al, in press). In fact the uncertainty in the Pyrus palaeo-column itself may reflect the fact that its was the first column in the area to breach. None of the other prospect faults have a throw that is sufficient to juxtapose the Katnook sandstone against the Pretty Hill sandstone reservoir.

Fault re-activation risking in the in-situ stress tensor using FAST shows that the Pyrus Fault is critically oriented in the in-situ stress field for re-activation. Hence the time window within which the Pyrus structure breached is interpreted to have occurred sometime since the displacement of the Katnook Sandstone against the Pretty Hill Sandstone and the present day. CO₂ concentrations above background levels measured across the interpreted surface location of the fault suggest that the fault is presently leaking which corroborates the notion of a fairly recent slip event or series of slip events occurring on this fault.

Although the presence of a palaeo-column at Pyrus remains speculative, these results explain why there is no live column at Pyrus.

Ladbroke Grove

The juxtaposition results for the Ladbroke Grove Fault show that the Ladbroke Grove column hosted by the Pretty Hill Formation reservoir in the footwall juxtaposes Units 3 and 4 of the Laira Formation in the hangingwall (Fig. 7b). Only very infrequent, discontinuous sandstone lenses of less than 5 m thickness are identified within these units (Fig. 6). Hence these Units have good juxtaposition sealing potential. It is thus interpreted that the Ladbroke Grove column is presently sealed by juxtaposition and thus is not dependant on shale veneer on the fault surface to seal the column. The possibility of a potential juxtaposition leak window across the fault, although unlikely, cannot be dismissed entirely due to stratigraphic uncertainty away from well control.

The Ladbroke Grove Fault shows evidence on seismic data of continual fault re-activation throughout its structural history similar to that observed on the Pyrus Fault. The Ladbroke Grove Fault must have still maintained its seal integrity despite being re-activated post-charge to be maintaining a column in the present day. Partial leakage of hydrocarbons up the fault may have occurred periodically by generation of permeable fracture networks by re-activation slip events on the fault plane under brittle conditions of rock deformation (Sibson, 1992). To explain the observed column in the present day seal integrity must have been restored by subsequent fracture re-healing. The field may have thus had a complex history of filling, leakage and refilling. Previous interpretation of a possible palaeo free water level 9 m below the FWL by Little (1996) is consistent with this interpretation. As there is a low risk of a sand-on-sand leak window being present across the Ladbroke Grove Fault, continual leakage across the fault, as is interpreted in the case of Pyrus Fault is unlikely.

Seismic interpretation of the Ladbroke Grove Fault indicates that the height of the column appears to be controlled by the change in geometry of the fault. The column is bound by the east–west trending part of the fault and the FWL, when projected onto the fault surface, coincides with the point on the fault plane were the strike changes from east–west to northwest–southeast. The FAST analysis indicates that the northwest–southeast part of the fault is critically oriented within the in-situ stress field for re-activation while the east–west part has a relatively lower risk of fault re-activation. It is therefore possible that the very recent slip event along the more critically oriented northwest–southeast trending part of the fault caused brittle fracturing resulting in leakage of hydrocarbons to the surface. Alternatively the point at which the fault abruptly changes strike may in itself be a zone of intense fracturing. Previous work has shown that kinks or bends in fault traces may represent the existence of two separate faults that have since adjoined to form a relay structure which are susceptible to fracturing and are thus high risk to fault seal integrity (Childs et al, 1997).

CONCLUSIONS

• Analysis of the across fault juxtaposition of lithology on the Ladbroke Grove Fault shows that the column, hosted by the Pretty Hill sandstone in the footwall, juxtaposes massive shale units in the hangingwall. Hence, the sealing of the column can be explained in terms of favourable juxtaposition.
• The Ladbroke Grove column is bound by an east–west trending part of the fault and the free water level (FWL) of the column is coincident with a change in fault orientation from east–west to northwest–southeast. Hence the column height at Ladbroke Grove seems to be related to the structural geometry of the fault.

• The assessment of recent fault re-activation risk in the in-situ stress tensor using the FAST technique shows that the northwest–southeast trending part of the Ladbroke Grove Fault is critically oriented in the in-situ stress field for re-activation. The east-west trending part of the fault however, has a relatively low risk of fault re-activation within the in-situ stress tensor. It is therefore possible that a recent slip event along the more northwest–southeast trending segment of the fault has created open permeable fracture networks in the fault zone, thus limiting the column extent to the east–west trending segment of the fault. This interpretation is corroborated by CO\(_2\) leakage data which suggests that the northwest–southeast trending segment of the fault is now leaking CO\(_2\) to the surface whereas the east–west trending fault segment is not leaking CO\(_2\) to the surface.

• The Pyrus Fault hosts an interpreted palaeocolumn in the Pretty Hill Sandstone reservoir within the footwall.

• Juxtaposition analysis indicates that the Pyrus Fault is not presently sealing by juxtaposition. The throw on the fault is sufficient to completely displace the Laira Formation top seal in the hangingwall past the Pretty Hill reservoir in the footwall resulting in juxtaposition of the Katnook Sandstone Member against the top of the Pretty Hill Sandstone reservoir at the apex of the trap.

• A relatively high shale gouge ratio (SGR) of 43% computed across this sand-on-sand contact at the top of the structure suggests that the fault should be capable of holding back a column by shale gouge over this potential juxtaposition leaky window.

• Re-activation of the Pyrus Fault subsequent to the timing of this sand-on-sand juxtaposition resulted in brittle fracturing of any shale gouge veneer that may have been present over this sand-on-sand contact resulting in across-fault leakage into the Katnook Sandstone and up the fault along permeable fracture networks. This sand-on-sand contact is likely to have continued to serve as a leaky window across the fault to the present day with subsequent charge to this trap being lost by across fault leakage and episodic leakage up the fault to the surface. This is corroborated by:
  — seismic data that shows that the fault has been continually active throughout its structural history;
  — a high risk of fault re-activation predicted by FAST on the Pyrus Fault;
  — the presence of significant shows within the Katnook Sandstone and basal Eumeralla Formation sands of the footwall; and
  — a CO\(_2\) anomaly over the Pyrus Fault suggesting that it is now leaking.

• A thorough understanding of fault seal integrity of traps therefore requires a systematic assessment of fault geometry, juxtaposition and fault damage in addition to stress-based methods of leakage prediction.

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**THE AUTHORS**

**Paul Lyon** graduated from the University of Birmingham with a BSc in applied geology in 2001. He commenced a PhD at the NCPGG (now Australian School of Petroleum) in 2002 investigating fault seal integrity in the onshore Otway Basin. He has worked on projects with the University of Lisbon, British Geological Survey, South Australian Department of Water Land and Biodiversity, Schlumberger and Petratherm Ltd. He has recently accepted a position with Shell (SIEP) as an exploration geologist in Rijswijk, The Netherlands. Member: AAPG, PESA, SPE, SEG, ASEG and EAGE.

**Peter Boult** is the chief petroleum geologist at PIRSA. He graduated with a BSc (Hons) from Leeds University UK in 1976 and a PhD (applied geology) from the NCPGG in 1997. He worked as a lecturer at the University of South Australia from 1987–97, but has been associated with the petroleum industry since 1980 having worked in Europe, the Middle East, Australia and Papua New Guinea. His interests are reservoir and seal evaluation.

**Max Watson** is a research fellow at the Australian School of Petroleum (formerly NCPGG). He completed a BSc at James Cook University in Townsville in 1998 and a BSc (Hons) at the NCPGG in 2000. His research focusses on alteration of reservoir systems by CO$_2$, reservoir diagenesis, seal alteration and CO$_2$ migration and leakage in the Otway Basin. He is part of the CO2CRC research group.

**Richard Hillis** is the State of South Australia Professor of Petroleum Geology and Mawson Professor of Geology and Geophysics at the University of Adelaide. He graduated with BSc (Hons) from Imperial College (London, 1985), and PhD from the University of Edinburgh (1989). His research interests are in petroleum geomechanics and sedimentary basin tectonics. He leads a group of nine researching these topics at the University of Adelaide. He has published about 80 papers, edited two books and has consulted to and run short courses for many Australian and international oil companies. Richard is a non-executive director of JRS Petroleum Research Pty Ltd and Petratherm Ltd. Member: AAPG, AGU, ASEG, EAGE, GSA, GSL, PESA, SEG and SPE.