Sealing by Shale Gouge and Subsequent Seal Breach by Reactivation: A Case Study of the Zema Prospect, Otway Basin

Paul J. Lyon
Australian School of Petroleum, University of Adelaide, Australia

Peter J. Boult
Australian School of Petroleum, University of Adelaide, Australia and also Department of Primary Industries and Resources South Australia, Adelaide, Australia

Richard R. Hillis
Australian School of Petroleum, University of Adelaide, Australia

Scott D. Mildren¹
Australian School of Petroleum, University of Adelaide, Australia

ABSTRACT

The Zema prospect, located in the Otway Basin of South Australia, hosts an interpreted 69-m (226-ft) paleohydrocarbon column. Two faults are significant to prospect integrity. The main prospect-bounding fault (Zema fault) shows a significant change in orientation along strike, with some parts of the fault trending northwest-southeast and other parts trending east-west, all at a consistent dip of about 70°. The fault shows a complex splay and associated relay zone at its western tip. An overlying fault shows a similar northwest-southeast trend.

Shale volume \(V_{\text{shale}}\) derived from the gamma-ray log was tied to seismic horizon data in order to model across-fault juxtaposition and shale gouge ratio on the Zema fault. Shale volumes of greater than 40% correspond with paleosol shale lithotypes identified in the core that are characterized by high mercury injection capillary entry pressures of 55 MPa (8000 psi), capable of supporting gas columns far beyond the

¹Present address: JRS Petroleum Research Pty. Ltd., Magill, Adelaide, Australia.
structural spillpoint of the trap. $V_{\text{shale}}$ values of 20–40% correspond to silty shale lithotypes characterized by mercury capillary entry pressures equivalent to gas column heights of less than 30 m (100 ft). Sands correspond with $V_{\text{shale}}$ values of less than 20%.

Juxtaposition modeling of the Pretty Hill reservoir interval that is displaced across the Zema fault against the Laira Formation seal demonstrates the existence of both sand-on-sand juxtaposition and sand-on-silty shale juxtaposition above the paleofree-water level. Hence, juxtaposition alone cannot explain the observed paleocolumn. It is therefore likely that fault damage processes on the fault plane were responsible for holding back the original 69-m (226-ft) column. Shale gouge ratio values show a gradual decrease from 32% at the top of the fault trap to less than 14% at the structural spillpoint. The fault damage zone is likely to consist of phyllosilicate framework rock types. Because the Zema trap was not filled to structural spillpoint, it is likely that the percentage of shale gouge in the fault zone not only provided the original sealing mechanism but also limited the original column height. This is supported by fault zone capillary entry pressures calculated from shale gouge ratio values, which indicate that the fault zone is only capable of supporting a maximum column height of 72 m (236 ft), just 3 m (10 ft) more than the interpreted column height of 69 m (226 ft).

Geomechanical analysis shows that the northwest–southeast-trending parts of the faults are optimally orientated in the in-situ stress field for reactivation. A spontaneous potential (SP) anomaly in the Zema-1 well, which was recorded in a northwest–southeast-striking fault damage zone through the seal, confirms the existence of open, permeable fracture networks. These are likely to have been generated by recent reactivation that caused the breach and subsequent leakage of the entire original hydrocarbon column.

**INTRODUCTION**

The Zema prospect is one of seven fault-bound prospects drilled in the Penola Trough in the Otway Basin of South Australia that have been interpreted as hosting a paleohydrocarbon column, i.e., a column that was once present but has since leaked away (George et al., 1998; Lisk et al., 2000). These paleohydrocarbon columns occur in the same play-type as five commercially producing gas fields: Katnook, Ladbroke Grove, Redman, Haselgrove, and Haselgrove South (Figure 1). The occurrence of both paleohydrocarbon columns and live columns in traps that are both full to spill and, in some cases, partially filled makes the Penola Trough an ideal location for testing and calibration of existing seal analysis methods. This case study of the Zema prospect is the first of a series of fault seal analyses to be undertaken in this area as part of a 3-yr project.

The Zema-1 well intersected a 65-m (213-ft) zone of paleohydrocarbons interpreted from drillstem test data, amplitude-vs.-offset seismic anomalies, ditch gas response, wire-line logs, and core (Boult et al., 2004) in the informally named Pretty Hill Sandstone reservoir of the Pretty Hill Formation. This paleohydrocarbon zone comprises a 50-m (160-ft) gas cap and a 15-m (49-ft) oil leg (Lovibond et al., 1995; Boult, 1997). The Pretty Hill Sandstone is regionally sealed by the overlying Laira Formation, which shows an average thickness of 400–500 m (1300–1600 ft) over the Zema prospect. The seal potential of the Laira Formation has been extensively studied. Boult (1997) deduced that fine shale paleosols in this formation form effective capillary top seals to hydrocarbon migration. These sealing units are abundantly distributed in the Laira Formation and show a high probability of being laterally continuous over prospects (Boult, 1997). For these reasons, initial top-seal risk in the Penola Trough is considered to be minimal. The presence of many breached columns in this area has thus been interpreted to be a fault-related seal issue (Hillis et al., 1995; Jones et al., 2000; Willink and Lovibond, 2001; Boult et al., 2002a).

Conventional fault seal analysis involves a first-order assessment of the seal potential caused by across-fault juxtaposition of different lithology types (Smith, 1966; Allan, 1989; Yielding et al., 1997), followed by a second-order analysis of the seal potential of the fault itself (Knipe, 1997; Yielding et al., 1997; Yielding, 2002). Shale volume estimates determined from well-log data are tied to seismic horizon data and projected onto fault plane surfaces in the modeling of across-fault juxtaposition (Downey, 1984; Watts, 1987; Jev et al., 1993). Predictive algorithms, such as shale gouge ratio (SGR) (Yielding et al., 1997) and shale smear factor (Lindsay et al., 1993; Gibson, 1994), are used to determine the
Sealing by Shale Gouge and Seal Breach by Reactivation

An assessment of the likelihood of subsequent breach of viable prospects through postcharge reactivation of faults is required in certain circumstances (Sibson, 1996; Mildren et al., 2002; Wiprut and Zoback, 2002; Jones and Hillis, 2003). Recently reactivated faults are known from outcrop studies to be associated with permeable fracture networks (Barton et al., 1995). Recent reactivation of faults in the Otway Basin, like many other Australian basins, is considered a key exploration risk (Boult and Jones, 2000; Mildren et al., 2002).

Jones et al. (2000) assessed the probability of fault reactivation in the Penola Trough using two-dimensional fault analysis seals technology (2-D FAST). Fault analysis seals technology is a technique that quantifies the relative risk of fault reactivation in terms of in-situ stress and rock properties (Mildren et al., 2002, 2005). Although FAST predictions of fault reactivation have been successfully calibrated to the present-day distribution of hydrocarbon columns in the Timor Sea (Mildren et al., 2002), 2-D FAST predictions of fault reactivation did not fully explain the distribution of paleocolumns in the Penola Trough (Boult et al., 2002a). This suggested that

**Figure 1.** Location and status of drilled hydrocarbon prospects in the Penola trough, Otway Basin, South Australia. A near top Pretty Hill Formation horizon is displayed. The dashed white line indicates the location of Figure 3.
mechanisms other than recent fault reactivation may be significant to hydrocarbon leakage. Boul et al. (2002a) proposed a mechanism of breach by fracturing of intact top seal caused by stress perturbations that occur locally around faults (Ramsey, 1967). Areas of high differential stress and, thus, high risk of cap seal breach can be predicted through stress modeling (Hunt and Boul, 2005).

We believe that to unequivocally calibrate the relatively new predictive methods of fault-related seal breach analysis in the Penola Trough, a thorough fault seal analysis is required, consisting of first-order fault geometry and juxtaposition analysis, a second-order analysis of fault plane properties, and an analysis of fault reactivation, using quantitative methods. A full and quantitative assessment of these parameters will allow us to fully constrain both the original sealing mechanisms in place and the influence of fault seal breach caused by recent fault reactivation. We present here the methodology and results of a uniquely customized fault seal analysis for the Zema prospect that should be applicable elsewhere in the Otway Basin.

Detailed structural interpretation using both seismic time data and pseudodepth-converted data (Lyon et al., 2004) was undertaken. A first-order analysis of juxtaposition (Allan, 1989; Yielding et al., 1997) is presented, together with a methodology of calibrating $V_{\text{shale}}$ predictions from the gamma-ray and spectral gamma-ray log to capillary entry pressures and lithological interpretation from core analysis. The SGR method (Yielding et al., 1997) was used to assess the likelihood of fault zone sealing caused by entrainment of shale gouge in the fault zone (Knipe, 1992). The minimum fault zone capillary pressure was calculated from SGR values computed on the fault plane for comparison with predicted buoyancy pressure gradients for the original column prior to breaching (Bretan et al., 2003). Reactivation potential was determined using three-dimensional (3-D) FAST to assess the risk of recent reactivation (Mildren et al., 2002, 2005).

**REGIONAL GEOLOGY**

The Otway Basin formed as a result of rifting and continental breakup of Australia and Antarctica. Rifting was initiated along the presently onshore part of the basin in the Late Jurassic (Lovibond et al., 1993) (Figure 2). The Penola Trough is one of a series of onshore half-graben structures that formed as a result of this initial rifting (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 (Finlayson et al., 1993) (Figure 1).
litharenite to feldspathic litharenite (Alexander, 1992; Little, 1996). The Laira Formation, which comprises interbedded siltstones, shales, and occasional sands, was deposited in an overbank to lacustrine environment (Kopsen and Scholefield, 1990). The Laira Formation has been subdivided into five units based on well correlation of algal content (Lovibond et al., 1993) (Figure 3).

The Casterton Formation and Crayfish Group show synsedimentary growth into many of the Early Cretaceous intrarift faults formed during the initial rifting phase. These intrarift faults strike east–west in the central part of the Penola Trough, but at the margins of the trough, the strike is predominantly northwest–southeast (Figure 1).

Cessation of rifting was coincident with a period of erosion on uplifted footwall escarpments marked by the locally angular unconformity surface at the top of the Crayfish Group. This was followed by thermal sag with widespread deposition of the Eumeralla Formation of as much as 2 km (1.2 mi) thickness (Figure 2) (Hill

**Figure 3.** Correlation of the Laira Formation units across Zema-1 and adjacent wells based on algal content and showing anomalously high gamma-ray values associated with unit 2 (information supplied in Lovibond et al., 1993). See Figure 1 for location.
and Durrand, 1993). Compaction of relatively thick Crayfish Group sediments up against the hanging walls of large half-graben-bounding faults, under the weight of the Eumeralla Formation, allowed synsedimentary faulting to penetrate the base of the Eumeralla Formation, despite the cessation of continental extension. Rifting between Australia and Antarctica was reinitiated in the Late Cretaceous, but the rifting depocenter shifted 50 km (30 mi) to the southwest of the Penola Trough, thus leaving the Penola Trough and similar depocenters as failed rift structures (Finlayson et al., 1993; Lovibond et al., 1993). The Eumeralla Formation was deposited in a fluvial lacustrine environment and consists of interbedded volcanogenic lithic sandstones, siltstones, coals, and claystones (Cockshell et al., 1995; Morton et al., 1995). Sediments of the overlying Sherbrook Group were deposited in the Late Cretaceous under fluvio-deltaic conditions and consist of frequent mudstone units and massive sandstone sediment packages (Morton et al., 1995). The Tertiary succession can be subdivided into massive sandstone sediment packages (Morton et al., 1993). The Eumeralla Formation was deposited in the Late Cretaceous under fluviodeltaic conditions and consists of interbedded volcanogenic lithic sandstones, siltstones, coals, and claystones (Cockshell et al., 1995; Morton et al., 1995). Sediments of the overlying Sherbrook Group were deposited in the Late Cretaceous under fluvio-deltaic conditions and consist of frequent mudstone units and massive sandstone sediment packages (Morton et al., 1995). The Tertiary succession can be subdivided into massive sandstone sediment packages (Morton et al., 1993). The Eumeralla Formation was deposited in the Late Cretaceous under fluviodeltaic conditions and consists of interbedded volcanogenic lithic sandstones, siltstones, coals, and claystones (Cockshell et al., 1995; Morton et al., 1995).

PREVIOUS STRUCTURAL INTERPRETATION

Previous structural interpretation in the area has commonly failed to recognize the complex kinematic relationships between older, Early Cretaceous synsedimentary faulting and younger, postrift faulting (Aburas and Boult, 2001; Boult et al., 2002a). Because of the structural complexity of fault geometries in the area (Chanthraprasert et al., 2001), the authors consider it important to understand the true depth geometries of both the main Zema prospect-bounding fault and any associated faulting. In the absence of prestack depth migration seismic data for the area, a laterally invariant velocity function was applied to the time-migrated seismic data to convert it to seismic data scaled by depth. The method describing the determination of the velocity function used in the depth conversion is beyond the scope of this chapter; for a full discussion of the technique, the reader is referred to Lyon et al. (2004). Both time-based and depth-based seismic profiles were used interactively in the workstation interpretation, together with variance slices that were computed for both seismic data sets. Interpretation made in the time domain was cross-checked with the depth interpretation to ensure that it was structurally valid. Further quality control of fault interpretation was undertaken using 3-D visualization and modeling software to eliminate inherent interpretation error.

Interpretation of four prominent seismic reflectors was undertaken after the fault geometries had been accurately mapped. The horizons interpreted were the unconformity surface at the top of the Laira Formation, the top of the Pretty Hill Formation, the top of the Eumeralla Formation, and a prominent reflector in the Sherbrook Group. The stratigraphic assignment of each horizon pick was validated by the creation of a synthetic seismogram derived from the Zema-1 sonic and checkshot log. The fault and horizon interpretation made on the depth-scaled seismic sections could be tied to the known depths of formation tops and fault interpretation in the Zema-1 well. Hence, the interpretation made in the depth domain was used in the subsequent fault seal analysis without the need to apply a more complex depth conversion to the time interpretation (e.g., Birmingham et al., 1985; Blackburn, 1986).

The depth interpretation model of the Zema prospect shows two major faults, which are significant to its trap integrity (Figure 4). Maximum displacements are found at the central parts of both faults, with a gradual decrease in displacement toward the fault tips. The abrupt change in throw observed at the western end of the main prospecting bounding Zema fault plane (referred to as the Zema fault herein) is caused by a fault splay (Figure 5). Although relay and fault splay intersections are generally considered to be critical to fault trap integrity (Childs et al., 1997), this fault splay occurs beyond the extent of the paleohydrocarbon column. It is therefore not thought to be significant to the trap geometry and is thus excluded from subsequent fault seal analysis.

From east to west, the Zema fault shows a variation in strike from east–west to northwest–southeast then to east–west (Figures 4, 5). Fault dips are fairly consistent, lying within a range of 60–70° NNE. The maximum throw for the top Pretty Hill Formation and top Laira Formation observed on the fault is 270 and 204 m (885 and 669 ft), respectively. A second fault directly overlies the northwest–southeast segment of the Zema fault, where it mimics the underlying Zema fault geometry (Figure 4). At the eastern end of this fault, however, it clearly splays away from the main Zema fault trend to a more east-southeast–west-northwest strike. The overlying fault has displaced both the top Eumeralla Formation.
and Sherbrook Group horizons. The maximum throw for the top Eumeralla Formation and Sherbrook Group horizons is 87 and 50 m (285 and 164 ft), respectively.

The height of the paleo-hydrocarbon column was determined from the difference in depth between the pick of the paleofree-water level (PFWL) in the well and the top of the structure in the depth model, which was found to be 69 m (226 ft). The 15-m (49-ft) thickness of the paleo-oil leg is constrained by the identification of the top and bottom of the oil zone in the Zema-1 well, but the implied 54-m (177-ft) height of the overlying gas cap is subject to the uncertainty associated with the depth conversion (see data limitations section). The PFWL lies 180 m (590 ft) above the structural spill point of the trap in the depth model.

**SHALE VOLUME**

Prediction of whether or not all or part of a fault plane is sealing in terms of juxtaposition and SGR requires an accurate determination of shale volume from log data. An estimate of the shale volume ($V_{\text{shale}}$) can be derived directly from the gamma-ray log by determining the maximum average gamma-ray values, assumed to be 100% shale (shale line), and the average minimum gamma-ray values, assumed to be 0% shale (sand line). All gamma-ray values can thus be assigned a percentage of $V_{\text{shale}}$ by assuming either a linear relationship or a nonlinear relationship of increasing $V_{\text{shale}}$ with increasing gamma-ray values (Rider, 2000). The relationship between gamma-ray values and $V_{\text{shale}}$ is dependent on the age of the units. For well-consolidated rocks, the relationship is more accurately described by a nonlinear function (Rider, 2000).

The anomalously high gamma-ray values that occur in unit 2 of the Laira Formation (Figure 3) were investigated on the basis that these elevated gamma-ray values may be caused by high quantities of organic matter instead of high clay content (Boul.t, 1997). The frequent adsorption of uranium by organic matter commonly results in anomalously high gamma-ray values that are not representative of true shaliness and therefore cannot be used to define a shale line. All units in the Crayfish Group in the Zema-1 well, including unit 2, could be correlated across to the Laira-1 well (Figure 3), where a spectral gamma-ray log was run. A crossplot of total gamma-ray values and thorium values from the spectral gamma ray over the Laira Formation interval in Laira-1 shows a good correlation (correlation coefficient = 0.8; Figure 6). Because the thorium log is a better indicator of shaliness than the total gamma-ray log (Rider, 2000), it can be reasonably inferred that the elevated values of the gamma-ray log in unit 2, which are associated with equally high Th values, are indeed caused by a genuinely high abundance of shale. Inspection of the neutron-density log in Zema-1 also shows that unit 2 is associated with the largest positive separation observed on the neutron-density log.

These observations confirm unit 2 as the most shale-rich unit. Unit 2 was therefore used to define the shale line at 156° API. The sand line was picked in the Pretty Hill Formation at 28° API. We can justify what may appear to be a rather high gamma-ray value for the sand line by extensive petrological work done by Little (1996), which had already shown that between 20 and 40% of the rock matrix of the Pretty Hill Sandstone in Zema-1 comprises feldspars and igneous rock.
fragments, and that generally less than 5% is detrital clay matrix. Thus, the relatively high gamma-ray value for this sand is caused by the nonclay matrix grains, which do not contribute to the formation of shale gouge. Furthermore, the good correlation between the gamma-ray and thorium values show that the gamma ray is a good indicator of shaliness for these lithology types.

The nonlinear conversion of gamma ray to $V_{\text{shale}}$ for consolidated rocks (Rider, 2000) was used to derive a $V_{\text{shale}}$ log:

\[
V_{\text{shale}} = 0.33 \left(2^{\frac{\text{GRI}}{\text{C0}}} - 1\right),
\]

where Gamma-ray Index (GRI)

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

$\text{GR(min)}$ is the minimum average gamma-ray value (sand line); $\text{GR(max)}$ is the maximum average gamma-ray value (shale line); and $\text{GR(log)}$ is the actual gamma-ray log value.

**CORE CALIBRATION**

The $V_{\text{shale}}$ log was used to subdivide the Laira and the Pretty Hill formations into 45 intraformational beds or isochores (Bouvier et al., 1989). This detailed lithological interpretation was necessary for a thorough juxtaposition analysis, because even a 1-m (3.3-ft) sand that was unfavorably juxtaposed across the fault could be crucial to initial fault seal integrity.

Each intraformational bed was also assigned a lithology type based on calibration with core. Figure 7 shows...
the interpretation of a cored interval through the base of the Laira Formation. An intra-Laira sand occurs at the top of the core. Below this sand, the core consists of predominantly silty shale with occasional thin interbeds of relatively clay-rich paleosol units. Mercury injection capillary pressure curves show that the dominant silty shale lithotype has an entry pressure of 2 MPa (300 psi), suggesting that it is only capable of holding back a total gas column height of 21 m (69 ft) (Figure 7). The clay-rich paleosol beds show an entry pressure of 55 MPa (8000 psi) and are thus capable of holding back a gas column far beyond the structural spillpoint of the trap. A comparison of the core with the Vshale log shows that the sandstone and silty shale lithologies have average Vshale values of 15 and 33%, respectively. Two thick paleosol units that are resolvable with the gamma-ray tool show average Vshale values of 46% and 48%. Thinner paleosol horizons identified in the core, in addition to those highlighted in Figure 7, are less than 80 cm (31 in.) thick and are thus beyond the resolution of the gamma-ray tool.

Intraformational beds of the Laira and Pretty Hill formations were classified into three broad lithology types for the purposes of qualitative juxtaposition analysis on the basis of this cross-comparison with the core. All beds with an average Vshale of less than 20% were assigned to a sand lithology type. Values between 20 and 40% were assigned to a silty shale lithology type with expected capillary pressures equivalent to just a few tens of meters of gas column height capacity. Values above 40% were assigned to a shale lithology type expected to have high capillary pressures capable of holding back a gas column to the structural spillpoint of the trap. The Laira Formation consists of a roughly equal mixture of both silty shale and shale, with four prominent thin interbeds of sandstone near its base. The Pretty Hill Formation consists of mostly sandstone with sparse interbeds of 10–15-m (33–49-ft)-thick silty shale.

**SHALE GOUGE RATIO**

Shale gouge ratio was computed along the fault plane using throw and average Vshale from the hanging wall and footwall (Yielding et al., 1997; Yielding, 2002). Figure 9a shows the shale gouge computation results for the slipped interval on the fault plane where the top Pretty Hill Formation horizon has been displaced. The SGR values over sand-on-sand, silty shale-on-sand, and silty shale-on-silty shale intervals show a gradual decrease from values as high as 34% at the top of the trap to values as low as 15% at the structural spillpoint.

Shale gouge ratio values from the top of the trap to the depth of the interpreted PFWL, sampled at 5-m (16-ft) intervals, were converted to fault zone capillary entry pressure (FZP) using the equation \( FZP = 10^{SGR/27-C} \) (Bretan et al., 2003) (Figure 9b). A C value of 0.5 was used, because the burial depth is less than 3 km (1.8 mi). If it is assumed that leakage results when the buoyancy pressure of the hydrocarbon column exceeds the minimum FZP on the fault plane (Bretan and Yielding, 2005), then these data can be used to predict the maximum

**JUXTAPOSITION**

The interpreted internal stratigraphy of the Laira and Pretty Hill formations in the Zema-1 well was isopached proportionally between the top Laira Formation and the top Pretty Hill Formation seismic horizons in the depth model, thus providing a detailed stratigraphic interpretation for the footwall and slightly thicker section in the hanging wall. The lateral continuity of sands is discussed under the data limitations section.

Figure 8 shows the mapped juxtaposition relationships for the slipped interval on the fault plane where the top Pretty Hill Formation horizon has been displaced. Of key significance is the occurrence of an intra-Laira Formation sand juxtaposed against Pretty Hill Formation reservoir sand above the PFWL. Furthermore, several occurrences of Laira Formation silty shale are also juxtaposed against Pretty Hill Formation sands that occur above the PFWL. These silty shale units show an average Vshale of approximately 32%, which is equivalent to the silty shale lithology types identified in the core through the base of the Laira Formation (Figure 7). It is therefore inferred that these silty shales are likely to have similar entry pressures and are thus unable to hold back a gas column greater than about 20 m (66 ft).

Fault juxtaposition relationships alone cannot explain the interpreted 69-m (226-ft) paleocolumn at Zema. Accordingly, the mechanical processes occurring in the fault damage zone were considered as a mechanism for sealing.
major slip plane coincident with the interpreted location of the fault in the depth model

very minor fault slip plane
fault ramp
subseismic fault slip plane

mercury Injection
Capillary Pressure Curves

300 psi = 2 MPa
Pressure (psig)

8000 psi = 55MPa
Pressure (psig)
column height sustainable by the fault zone. The interpreted buoyancy gradients for both gas (8 kPa/m) and oil (4.3 kPa/m) were calculated using subsurface density measurements made in adjacent wells (oil density = 0.53 g/cm³; gas density = 0.143 g/cm³; and water density = 0.97 g/cm³). The buoyancy gradients were used to predict the maximum column height for a gas cap associated with the known 15-m (49-ft) oil leg based on the observed FZP values (Breton et al., 2003). The predicted total maximum column height is 72 m (236 ft) (Figure 9b). The predicted point of leakage is near the top of the fault where SGR values are greater than 30% (Figure 9b). This predicted column height interpreted from FZP values is only 3 m (10 ft) greater than the interpreted paleocolumn height of 69 m (226 ft).

Therefore, shale gouge developed on the fault plane is a plausible mechanism to explain the primary entrapment of the hydrocarbon column at Zema. Furthermore, the filling of the trap down to the PFWL may have been controlled by capillary leakage related to the amount of shale gouge in the fault zone.

**FAULT CHARACTERIZATION**

A dipmeter interpretation was used to determine the position of the Zema fault interpreted on seismic data in the Zema-1 well, so that the fault rock properties could be investigated from wire-line logs (Figure 7). Distinct zones of abrupt change in dip and strike are present that indicate that the fault plane, as identified on seismic data, consists of multiple slip planes at the resolution of the dipmeter. The main slip plane interpreted on the dipmeter occurs at 1890 m (6200 ft), near the base of the Eumeralla Formation, consistent with the interpreted location of the fault in the depth seismic interpretation (Figure 4). The 8-m (26-ft) zone of faulting that is interpreted from the dipmeter at 2040 m (6692 ft) corresponds to a distinct spontaneous potential anomaly and represents the lower fault of a relay ramp that dips northeast and has a strike of 300° (northwest–southeast). The spontaneous potential anomaly suggests that this fault surface and slip plane (beyond the resolution of the seismic data) is permeable. However, spontaneous potential effects, which are associated with the main fault plane, are disguised by the more frequent sandstone beds at the base of the Eumeralla Formation.

**REACTIVATION ASSESSMENT (FAST)**

The reactivation potential of the Zema fault analysis seals technology and the overlying fault was assessed using Fault Analysis Seals Technology (FAST) (Mildren et al., 2002, 2005). A brief overview of the technique is given here, but for a more detailed discussion, the reader is referred to Mildren et al. (2005). FAST provides an assessment of the likelihood of a fault to reactivate in the present-day stress field. The reactivation potential is quantified in terms of the increase in pore pressure (ΔP) 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. Three inputs are required for FAST analysis: the failure envelope, the in-situ stress field, and the fault orientation data (Figure 10a, b).

The following stress gradients in the Penola Trough were determined by Jones et al. (2000) for a depth range of 2500–3000 m (8200–10,000 ft) and were used to determine the 3-D Mohr circle used in the FAST analysis herein:

- minimum horizontal stress ($\sigma_h$) = 16.1 MPa/km.
- overburden stress ($\sigma_v$) = 22.4 MPa/km.
- maximum horizontal stress ($\sigma_h$) = 28.7 MPa/km.
- pore pressure ($P$) = 9.8 MPa/km.
- maximum horizontal stress ($\sigma_h$) orientation = 156° N.

The failure envelope was determined using the results from triaxial testing of a core sample through a cataclasite fault zone in the Pretty Hill Formation in the Banyula-1 well (Dewhurst and Jones, 2002) (see Figure 1 for location):

$$\tau = 5.40 + 0.78 \sigma'_n$$

where $\tau$ is shear stress at failure, and $\sigma'_n$ = effective normal stress (i.e., $\sigma_n - P$), with all pressure units in megapascals.

The above criteria were then used to assign a reactivation risk (ΔP) to the 3-D fault surface elements of the Zema fault and overlying fault (Figure 10c). The northwest–southeast-trending part of the Zema fault is associated with ΔP values in the range of 6–7 MPa/km (red colors) and is critically orientated in the in-situ...

**Figure 7.** Zema-1 caliper (CALS), gamma-ray (GR), spontaneous potential (SP), and dipmeter logs. Interpretation of the cored interval through the base of the Laira Formation, together with the interpreted $V_{shale}$, the main paleosol zones and mercury injection capillary pressure (MICP) curves for the core (bottom). The dipmeter interpretation through the fault zone is also shown (top). A spontaneous potential anomaly associated with a subseismic fault slip plane is highlighted. CALS = caliper logs; KB = Kelly Bushing.
**Figure 8.** View from the hanging wall toward the footwall of juxtaposition modeling results for the slipped interval on the fault plane, where the top Pretty Hill Formation reservoir has been displaced (left). The position of points X and Y are indicated on the location reference diagram (right). PFWL = paleofree-water level.

**Figure 9.** (a) Shale gouge ratio values for the interval on the fault plane where the top Pretty Hill Formation reservoir has been displaced. The position of points X and Y are indicated in Figure 8. (b) The fault zone capillary entry pressure (FZP) profile, calculated from SGR values sampled at 5-m (16-ft) increments from the top of the trap to the PFWL. The predicted maximum buoyancy profile and, thus, predicted maximum column height are shown.
stress field for reactivation. The more east–west-trending part of the fault generally shows values greater than 12 MPa/km and are thus less critically oriented for reactivation (blue colors). The overlying fault shows the lowest ΔP values that range from 5 to 5.5 MPa/km over the northwest–southeast-striking zone, where it directly overlies the northwest–southeast-striking part of the Zema fault.

DATA LIMITATIONS

Unavoidable limitations are imposed on any fault seal analysis by the available data. Structural uncertainty arises from the limited resolution of seismic data, which prevents the incorporation of subseismic structural elements that make up the fault zone model (Childs et al., 1996, 1997; Doughty, 2003;...
Koledoye et al., 2003), such as the relay zone and multiple slip planes, which were identified on the dipmeter log. Further uncertainty exists in determining the scale of heterogeneity in terms of fault zone composition and thickness (Fisher and Knipe, 1998; Sperrevik et al., 2002; Yielding, 2002). Although algorithms such as SGR can provide a good estimate of the average shale content of fault zones at the seismic scale, it remains difficult to upscale the heterogeneities of fault zones as observed in both log data and core samples into a meaningful and representative fault seal model. Furthermore, the fluid-flow properties of fault zones (Gibson, 1998; Weher et al., 2000), which may be controlled by thermal history and effective stresses at the time of deposition and postdeposition (Fisher and Knipe, 1998; Fisher et al., 2003), must also be considered. In addition to these generic limitations of fault seal analysis, several limitations that are specific to the data quality and methodology adopted in this analysis of the Zema prospect exist.

1) There is incomplete 3-D seismic data coverage over the prospect. The 3-D survey spans much of the east–west-trending part of the fault, to the west of the Zema-1 well (Figures 4, 5). Furthermore, the 3-D coverage of the prospect is at the edge of the 3-D St. George survey and is therefore not optimally migrated. The fault has been interpreted using 2-D data to the east of the Zema-1 well. The existence of additional relay zones and fault splay structures, similar to the one identified in the 3-D survey (Figure 5), are not discernable from the 2-D seismic data.

2) Potential error in the magnitude of throw on the Zema fault is highly probable because of the nature of the depth conversion used (Lyon et al., 2004) and also because of possible interpretation error limited by the relatively poor seismic resolution at this depth. A sensitivity analysis was undertaken by constructing a triangle diagram (e.g., Knipe, 1997) to assess how a conservative error margin of ±25 m (±82 ft) in throw would affect the predictions of across-fault juxtaposition relationships and SGR (Figure 11). The results show that potentially leaky juxtaposition of sand-on-sand and sand-on-silty shale would still be expected in the 25-m (82-ft) throw error margins. Figure 11 clearly shows that a throw in the order of 500 m (1600 ft) magnitude is needed to result in a viable juxtaposition seal of shale-on-sand for a 69-m (226-ft) column. No significant change to the SGR values in the specified 25-m (82-ft) throw error margin exist.

3) The sand line picked in the Pretty Hill Formation may have led to a slight overestimation in the $V_{\text{shale}}$ calculation, because petrological analysis of the Pretty Hill Sandstone typically shows 5% interstitial clays (Little, 1996). It is therefore postulated that even the lowest gamma-ray values in the Pretty Hill Formation may not truly represent a 0% shale line.

4) The $V_{\text{shale}}$ curve requires more mercury injection capillary pressure data points to be confident of precise calibration of $V_{\text{shale}}$ to capillary entry pressure. However, relating the observations made in core and mercury injection capillary pressure data
to the $V_{\text{shale}}$ curve demonstrated in this chapter does provide a useful reference for qualitative assessment of juxtaposition relationships.

5) The degree to which there is lateral variation in lithology type along the fault plane and away from well control limits the analysis. The sands that were cored at the base of the Laira Formation (Figure 7) are correlatable as far as the Laira-1 well; however, more detailed stratigraphic data or analyses are required to determine the lateral continuity of other units.

6) Uncertainty in upscaling laboratory-derived geomechanical fault rock properties to the seismic scale of the FAST analysis exists. In this case, we have used data from a cataclasite in the Pretty Hill Formation in Banyula-1, which is not necessarily representative of the predicted phyllosilicate framework fault rock predicted for the Zema fault above the PFWL.

A conservative range has been defined for the potential error in throw. However, the contribution in terms of quantitative error of other uncertainties to the cumulative error of the analysis is difficult to determine. The fact that the predicted column height obtained from SGR values (Figure 9b) is only 3 m (10 ft) larger than the interpreted paleocolumn height from the structural interpretation suggests an overall reliability in the first- and second-order fault seal analysis.

The sensitivity analyses described in Mildren et al. (2005) show significant changes to absolute $\Delta P$ values from FAST analysis when varying the failure envelope used. There is, however, no change to the fact that the northwest-southeast parts of the fault are critically oriented in the in-situ stress field for reactivation.

**DISCUSSION**

Our structural interpretation shows the existence of two distinct fault planes associated with the Zema prospect. The slightly thicker Crayfish Group in the hanging wall of the Zema fault confirms it formed as a synsedimentary fault in the Early Cretaceous. The overlying fault shows no synsedimentary deposition, and the initiation age of the fault is thus difficult to constrain. However, the geometry of the overlying fault mimics the geometry of the underlying Zema fault over its northwest-southeast-trending section. This may be caused by stress perturbation in the cover, because of the Zema fault, which, in turn, may be related to its reactivation.

The results of juxtaposition analysis show that both sand-on-sand and sand-on-silty shale zones of juxtaposition occur above the interpreted PFWL. The sand-on-sand juxtaposition zone has a high potential for leakage (Allan, 1989). The silty shale lithology shows a similar $V_{\text{shale}}$ value to the silty shale lithology identified in the core and is therefore likely to be only capable of holding back a gas column of just over 20 m (66 ft). It is therefore suggested that juxtaposition relationships alone cannot explain the retention of a 69-m (226-ft) column. However, it must be stressed that the simple assumption that sand-on-sand juxtaposition is nonsealing is not always correct. Fault damage zones in clean sandstone reservoirs can be associated with quartz-cemented cataclasites (Fisher et al., 2000, 2003) that are capable of supporting large columns. Indeed, an example of such a cataclasite zone was intersected in the Pretty Hill Formation at Banyula-1 (Jones et al., 2000; Dewhurst and Jones, 2002). Cataclasism and quartz cementation may be the dominant fault rock deformation processes in the Pretty Hill Formation, where sandstones have slipped past each other. However, where the Laira Formation has been downthrown against the Pretty Hill Formation (the critical part of the fault zone to trap integrity), the fault zone is unlikely to consist of well-developed zones of cataclasite over sand-on-sand intervals. The fault rock types will instead be dominated by phyllosilicate framework rock types based on the observed SGR range of 18–32% (Fisher and Knipe, 1998). This viewpoint is further supported by the recognition of a phyllosilicate framework fault rock in a core from Jacaranda Ridge-1, where the Pretty Hill Formation is more shaly (see Figure 1 for location).

We suggest that the 32–18% shale gouge that developed along the slipped interval between the Laira and Pretty Hill formations was responsible for holding back the original 69-m (226-ft) hydrocarbon column. Furthermore, it is possible that the extent of shale gouge development in the fault zone limited the height of the column to only 69 m (226 ft). This hypothesis is supported by Figure 9b, which shows that predicted fault zone capillary entry pressures calculated from SGR values predict a maximum hydrocarbon column height of 72 m (236 ft) for a 15-m (49-ft) oil leg based on the buoyancy gradients of the gas and oil phases calculated in nearby wells (Boult, 1997). Leakage is predicted to occur near the top of the fault, where the SGR values are greater than 30%. The fact that there is just a 3-m (10-ft) difference in the predicted column height from SGR values and the interpreted paleocolumn height suggests that it is shale gouge in the fault zone that limited the column height. Lack of charge may also have been the limiting factor. However, this is considered unlikely, because the live hydrocarbon columns at Redman, Katnook, Haselgrove, and Haselgrove South (Figure 1) all lie within 15 km (9 mi) of Zema and are full to structural spillpoint. Considering the evidence of abundant charge in the area and maturity modeling (Boult et al., 2004), it is suggested that the trap may have experienced more than one episode of capillary leakage of part of the gas column,
where added buoyancy pressure from additional hydrocarbon charge was sufficient to exceed the fault zone capillary pressure of the fault (Schowalter, 1979; Fisher et al., 2001).

Fault analysis seals technology indicates that the prospect-bounding northwest–southeast part of the Zema fault is critically oriented in the in-situ stress field for reactivation, associated with relatively low $\Delta P$ values of 6–7 MPa/km. Furthermore, the recognition of a spontaneous potential anomaly within part of a similarly oriented fault zone through the Laira Formation seal in Zema-1 indicates that at least part or parts of the fault zone are likely to be presently permeable (Figure 7). Recent reactivation is therefore likely to have breached the original shale gouge fault seal, causing the entire 69-m (226-ft) column to leak away. Although fault reactivation is the most likely explanation for the breach of the trap based on these observations, the authors do not dismiss the possibility of intact cap seal fracturing as a breach mechanism (Boulton et al., 2002b) discussed in more detail in Mildren et al. (2005) and Hunt and Boulton (2005).

Interestingly, the lowest $\Delta P$ values occur on the overlying fault and not the main Zema fault. Reactivation may have occurred preferentially along this more critically stressed fault, which may also extend down to the top of the reservoir as a subsurface feature. Perhaps growth of these younger faults is soft-linked to the reactivation of the underlying older faults. These younger faults, which are widespread throughout the upper sedimentary succession of the Penola Trough, have, to date, received little attention in the reactivation risking of fault-bound prospects, despite the fact that many are critically orientated for reactivation. The authors therefore stress the importance of a more holistic approach to reactivation risk, which accounts for faults in the upper section that may not necessarily be identified on seismic data at the reservoir level, but which may have propagated downward, causing subsurface fracturing through the cap rock.

A holistic risking method of assessing reactivation in regions such as the Penola Trough therefore demands two considerations: first, a detailed knowledge of both fault geometry and fault kinematics; second, as fault rock properties are strongly controlled by host rock lithology, throw, effective stress, and temperature history. Early Cretaceous synrift faults and shallower postrift faults are likely to be characterized by very different fault rock properties and, thus, different geomechanical properties. Future reactivation risking using FAST in the Otway Basin should attempt to consider these differences through the use of varying failure envelopes (see Mildren et al., 2005).

Further fault seal analysis of breached and intact columns in the Penola Trough will be undertaken to systematically assess juxtaposition, fault damage, and reactivation potential. The establishment of empirical calibrations of SGR to paleo- and present column height and of fault geometry to reactivation potential using FAST across numerous traps will reveal which are the critical risks.

**CONCLUSIONS**

- The Zema prospect is host to an interpreted paleohydrocarbon column. A paleofree-water level is identified at 69 m (226 ft) below the top of the trap, which is 200 m (660 ft) above the structural spillpoint.
- $V_{\text{shale}}$ estimates derived from the gamma-ray log used in this study are calibrated to lithology type and capillary pressure data from core analysis. $V_{\text{shale}}$ values of greater than 40% correspond with paleosol shale lithotypes in core that have capillary entry pressures of 55 MPa (8000 psi) and are thus capable of supporting gas columns beyond the structural spillpoint of the trap. $V_{\text{shale}}$ values of 20–40% correspond with silty shale lithotypes associated with capillary entry pressures equivalent to gas column heights of less than 30 m (100 ft). Sands correspond with shale volumes of less than 20%. The excellent correlation of the gamma-ray log and thorium log in an adjacent well confirms the reliability of the $V_{\text{shale}}$ values as a means of estimating shale content of these rock types.
- Across-fault juxtaposition modeling of the slipped interval of the top Pretty Hill Formation horizon shows several sand-on-sand and sand-on-silty shale windows that occur above the PFWL. Hence, juxtaposition alone cannot explain the observed paleocolumn.
- Shale gouge ratio values show a range of 32–18% over the slipped interval of Pretty Hill Sandstone reservoir, characteristic of a phyllosilicate framework rock-type fault zone (Fisher and Knipe, 1998). Fault zone capillary entry pressures calculated from SGR values predict a maximum hydrocarbon column height of 72 m (236 ft) for a 15-m [49-ft] oil leg and a 57-m [187-ft] gas cap) based on the buoyancy gradients of the gas and oil phases calculated in nearby wells. The critical leak point is at the top of the prospect-bounding fault zone, where SGR values are greater than 30% (Figure 9b). This predicted column height of 72 m (236 ft) is in close agreement with the paleocolumn height of 69 m (226 ft), which is determined from the structural interpretation and well data. This supports the interpretation that the shale gouge in the fault zone was responsible for entrapment of the original column. It also suggests that the column height may have been limited by capillary leakage related to the amount of shale gouge in the fault zone.
Acknowledgments

Peter Bretan, Andrew Davids, Richard Suttill, and Paul Theologou are thanked for their constructive reviews. Origin Energy and its joint venture partners are thanked for the provision of 3-D seismic data and regional near top Pretty Hill Formation horizon. All staff and students at the Australian School of Petroleum, University of Adelaide, are thanked for advice, guidance, and sharing of technical expertise. We particularly acknowledge the key contribution made by fellow researchers in the Stress Group (Australian School of Petroleum) and the Australian Petroleum Cooperative Research Center. All staff members at Badleys Geoscience Ltd. are thanked for their excellent software support and guidance and provision of Traptester software. Jerry Meyer of JRS Petroleum Research Pty. Ltd. and Quentin Fisher of Rock Deformation Research, University of Leeds, are also thanked for their informative comments and advice. Primary Industries and Resources of South Australia Publishing Services are thanked for their assistance in the drafting of Figures 1–3 and 7.

References Cited

Childs, C., J. J. Walsh, and J. Watterson, 1997, Complexity


Lindsay, N. G., F. C. Murphy, J. J. Walsh, and J. Watterson, 1993, Outcrop studies of shale smear on fault surfaces: International Association of Sedimentologists Special Publication 15, p. 113–123.


Sealing by Shale Gouge and Seal Breach by Reactivation

197


