FAST: A New Technique for Geomechanical Assessment of the Risk of Reactivation-related Breach of Fault Seals

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ABSTRACT

Postcharge fault reactivation may cause fault seal breach. We present a new methodology for assessment of the risk of reactivation-related seal breach: fault analysis seal technology (FAST). The methodology is based on the brittle failure theory and, unlike other geomechanical methods, recognizes that faults may show significant cohesive strength. The likelihood of fault reactivation, which is expressed by the increase in pore pressure ($\Delta P$) necessary for fault to reactivate, can be determined given the knowledge of the in-situ stress field, fault rock failure envelope, pore pressure, and fault geometry. The FAST methodology was applied to the fault-bound Zema structure in the Otway Basin, South Australia. Analysis of juxtaposition and fault deformation processes indicated that the fault was likely to be sealing, but the structure was found to contain a residual hydrocarbon column. The FAST analysis indicates that segments of the fault are optimally oriented for reactivation in the in-situ stress field. Microstructural

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evidence of open fractures in a fault zone in the subsurface in an offset well and an SP (self-potential) anomaly associated with a subseismic fault cutting the regional seal in the Žema-1 well support the interpretation that seal breach is related to fracturing.

**INTRODUCTION**

Fault sealing caused by juxtaposition and deformation processes has received considerable attention, and techniques for the analysis of such, e.g., Allan diagrams, juxtaposition diagrams, and shale smear algorithms, are widely applied (Allan, 1989; Knipe, 1997; Bretan et al., 2003). Well-constrained lithological and juxtaposition data, tied to seismically observable fault zones, can locate potentially leaking sand-on-sand contacts across faults and predict whether such sand-on-sand contacts are likely to be sealed because of deformation processes such as cataclasis or shale smearing (Jev et al., 1993; Hippler, 1997; Fisher and Knipe, 1998). However, whereas such analyses can define the sealing potential of faults that have been inactive since hydrocarbon charge, they do not incorporate the potential for seal breach because of fault reactivation subsequent to charge.

Abundant evidence shows that faults and fractures provide high-permeability conduits for fluid flow during deformation in the brittle crust (e.g., Sibson, 1994; Barton et al., 1995; Dewhurst et al., 1999). Juxtaposition or deformation process seals may be breached if the fault is reactivated subsequent to hydrocarbons charging the trap (Jones and Hillis, 2003). Seal breach caused by fault reactivation has been recognized as a critical risk in the Australian context. For example, in the Timor Sea region, Neogene fault reactivation related to collision between the Australian and Southeast Asian plates has breached many Jurassic or older paleotrap (O’Brien and Woods, 1995; Hillis, 1998; Shuster et al., 1998).

The relative likelihood of fault reactivation can be assessed given the knowledge of the prevailing stress field, fault orientation, pore pressure, and the failure envelope for the fault rocks. Morris et al. (1996) defined slip tendency based on the ratio of shear stress to normal stress acting on a fault surface. Ferrill et al. (1999) defined dilation tendency based on the normal stress acting on a fault plane normalized to the differential stress. Calculations of slip and dilation tendency were used to assess the likelihood of fault reactivation at the proposed high-level radioactive waste repository site at Yucca Mountain, Nevada. Wiprut and Zoback (2000) determined the increase in pore pressure required to induce reactivation of a normal fault in the Visund field, northern North Sea, assuming cohesionless frictional failure. Finkbeiner et al. (2000) assessed the height of hydrocarbon columns that could be sustained without inducing shear or tensile failure on trap-bounding faults in the Gulf of Mexico. These and related studies of the relationship between stresses and fault reactivation and permeability (e.g., Barton et al., 1995; Hickman et al., 1997) assume that the failure envelopes for fault rocks are described by a cohesionless friction law of the Byerlee (1978) type. However, frictional sliding experiments on cohesionless joints or saw-cuts through rocks of the type summarized by Byerlee (1978) do not describe the failure envelopes for cemented fault rocks that may exhibit significant cohesion (Dewhurst and Jones, 2002; Jones et al., 2002).

An alternative geomechanical parameter for assessing the risk of fault reactivation and associated seal breach is presented herein that can incorporate the cohesive strength of faults and, in a single parameter, express the risk of shear or tensile failure. The methodology is applied to the Žema structure in the Otway Basin, South Australia, which contains a fault-bound residual column. The technique can be readily modified to consider areas where shear or tensile failure of intact cap rock presents the key geomechanical risk, either because fault rocks are stronger than intact cap seal rocks or because preexisting faults are misoriented for reactivation. Prior to introducing the new approach, this chapter outlines the background concept of structural permeability and summarizes previously used geomechanical parameters for assessing fracture-related seal breach.

**STRUCTURAL PERMEABILITY**

Our approach to the geomechanical risking of reactivation-related fault seal breach is based on the concept of structural permeability (Sibson, 1996). Structural permeability is the permeability created by the interaction of various brittle structures (tensile fractures, shear fractures, and hybrid fractures; Figure 1). Such structures are generally created by the pressure of the infiltrating fluids and can be represented by failure criteria expressed in terms of pore pressure (Sibson, 1996) (Table 1). The theory of hybrid fracture generation is relatively contentious. Hybrid fractures can be considered to be multiple jointing events instead of tensile fractures with a shear component (Engelder, 1999). However, the Coulomb–Mohr envelope is still considered to be a valid predictor of failure in the tensile region as shown by Brace’s experiments (Brace, 1960; Engelder, 1999). The method presented herein is removed from the theory of hybrid fracture generation and is used to predict brittle failure instead of the form by which it is manifested.
Fracture-related seal failure has widely been considered to occur solely because of tensile fracturing (also termed natural hydraulic fracturing), whereby increasing pore fluid pressure reduces the minimum effective stress to below the tensile strength of the rock (e.g., Palciauskas and Domenico, 1980; Ozkaya, 1984; Bell, 1990; Engelder and Lacazette, 1990; Miller, 1995). Hence, Watts’ (1987) explanation of seals that fail by fracturing is hydraulic seals. Such tensile or natural hydraulic fracturing has, for example, been invoked to consider cap rock leakage in the North Sea (Caillet, 1993; Gaarenstroom et al., 1993; Caillet et al., 1997; Grauls, 1997). As discussed below, tensile fracturing can only occur with increasing pore-fluid pressure if differential stress is relatively low (Figure 1; Table 1; $\mu_s$ is the static friction coefficient along an existing plane of weakness; and $\mu_i$ is the internal coefficient of rock friction for intact rock.

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Barton et al. (1995) combined in-situ stress measurements with information on the orientations of hydraulically conductive fractures and faults in three wells in the southeastern United States and demonstrated that fractures and faults optimally oriented for shear reactivation are the most important permeability conduits. Wiprut and Zoback (2002) analyzed four fields in the northern North Sea, concluding that faults that are critically stressed in the current stress field (i.e., capable of slipping) tend to leak, whereas those that are not critically stressed are more likely to be sealing. Given the evidence suggesting that both tensile and shear fractures rupture to cause seal breaching, it is critical that any methodology for assessing the risk of seal breach because of reactivation incorporate the influence of both these elements of structural permeability.

Following Sibson (1996), we assume a composite Griffith–Coulomb failure envelope (Figure 1). Hence, tensile failure is predicted where differential stress is relatively low (Sibson, 1996). If $4T < \sigma_1 - \sigma_3 < 6T$, hybrid tensile-shear failure is predicted, and if $\sigma_1 - \sigma_3 > 6T$, shear failure is predicted. If the cohesive strength of a reactivated fault zone is zero, the failure envelope passes through the origin of the normal and shear stress plot, and reactivation in shear is the only possible

**Figure 1.** The effective normal ($\sigma_n'$) and shear ($\tau$) stresses leading to shear and tensile fracturing assuming a cohesionless Coulomb failure envelope ($\tau = \mu \sigma_n'$) for shear reactivation of a preexisting fracture and a composite Griffith ($\tau^2 - 4T \sigma_n' - 4T^2 = 0$)–Coulomb ($\tau = C + \mu \sigma_n'$) failure envelope for intact rock. The upper diagrams are schematic illustrations of the orientations of tensile and shear fractures in a rock sample. Shear fracturing occurs where differential stress (σ1–σ3, the diameter of Mohr circle) is relatively large compared to the tensile or cohesive strengths and tensile fracturing at relatively lower differential stress. Symbols are as in Table 1; $\mu_s$ is the static friction coefficient along an existing plane of weakness; and $\mu_i$ is the internal coefficient of rock friction for intact rock.

**Table 1.** Brittle failure criteria expressed in terms of pore pressure ($P$) and necessary differential stress conditions. Criteria assume a Composite Griffith–Coulomb failure criterion, whereby $C$ (cohesion) ~ $2T$ (tensile strength). The criteria apply to intact rock or reactivation of preexisting fractures, provided that the appropriate values of $T$, $C$, and $\mu$ (coefficient of friction) are used. After Sibson (1996).

<table>
<thead>
<tr>
<th>Failure Mode</th>
<th>Criterion</th>
<th>Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile (hydraulic)</td>
<td>$P = \sigma_3' + T$</td>
<td>$(\sigma_1 - \sigma_3) &lt; 4T$</td>
</tr>
<tr>
<td>Hybrid tensile and shear</td>
<td>$P = \sigma_3' + (4T^2 - \tau^2)/4T$</td>
<td>$4T &lt; (\sigma_1 - \sigma_3) &lt; 6T$</td>
</tr>
<tr>
<td>Shear</td>
<td>$P = \sigma_3' + (C - \tau)/\mu$</td>
<td>$(\sigma_1 - \sigma_3) &gt; 6T$</td>
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mode of failure, irrespective of the differential stress. Following experimental data by Handin (1969), Sibson (1996, 1998) recognized the influence of shear reactivation and noted that tensile fractures can only form and provide conduits for fluid flow, where

- rocks are intact and devoid of faults
- existing faults become severely misoriented for shear reactivation
- existing, favorably oriented, faults have regained cohesive strength because of cementation

We add to this last point, “or where the faulting process has resulted in a zone with significant cohesive strength.” Faulting may involve processes such as cataclasis with quartz cementation that result in significant cohesion and, therefore, tensile strength (as seen, for example, in the case study presented below from the Otway Basin).

GEOMECHANICAL PARAMETERS FOR ASSESSING THE RISK OF REACTIVATION-RELATED SEAL BREACH

The first introduced geomechanical parameters for assessing the risk of fracture-related seal breach assumed that such was caused by tensile failure of the cap rock (Watts, 1987; Caillet, 1993; Gaarenstroom et al., 1993), and thus, they were based on the criterion for tensile failure (Table 1). For example, Gaarenstroom et al. (1993) introduced the concept of retention capacity, which is given by the difference between the minimum horizontal stress and pore pressure (Figure 2). Retention capacity is thus the effective minimum horizontal stress ($\sigma_{h0}^s$). A positive retention capacity (or $\sigma_{h0}^s$) reflects the additional pore pressure (or hydrocarbon column height) that can be developed prior to tensile failure by natural hydraulic fracturing. If retention capacity is zero, then tensile fractures would develop if the rock had no tensile strength. Retention capacity only considers the risk of tensile (and not shear) failure and does not incorporate (tensile) rock strength.

In recognition of the fact that critically stressed shear fractures present conduits for fluid flow, Morris et al. (1996) introduced the concept of slip tendency, which is the ratio of shear stress to effective normal stress acting on a fault and expresses the likelihood of slip on a cohesionless fault (Figure 2). To assess risk caused by both shear and tensile fractures, Ferrill et al. (1999) used slip tendency and dilation tendency. The latter risks the likelihood of dilation (tensile reactivation) of a fault on a linear scale from zero (if $\sigma_1$ is normal to the fault) to one (if $\sigma_3$ is normal to the fault; Figure 2). Slip and dilation tendency can be used together to geomechanically risk the likelihood of fault seal breach caused by shear and tensile fracturing. However, two separate parameters, neither of which incorporates rock strength, must be assessed.

The Coulomb failure function was used by Castillo et al. (2000) to risk fault seal breach caused by reactivation in the Australian Timor Sea. The Coulomb failure function is the difference between the shear stress acting on a fault and that required to cause failure on a cohesionless fault (Figure 2). A negative Coulomb failure function thus implied a stable fault, whereas a positive Coulomb failure function was associated with low fault seal integrity. Wiprut and Zoback (2002) used the critical pressure perturbation to risk fault seal breach caused by reactivation in the northern North Sea. The critical pressure perturbation is the increase in pore pressure required to reduce the effective normal stress to the value that would cause slip on a cohesionless fault (Figure 2). The Coulomb failure function and the critical pressure perturbation both incorporate the coefficient of sliding friction on a fault in assessing its risk of shear reactivation. However, they do not allow for any cohesive strength on preexisting faults nor for the development of tensile fractures.

FAST: A NEW GEOMECHANICAL PARAMETER FOR ASSESSING THE RISK OF REACTIVATION-RELATED SEAL BREACH

We propose a new geomechanical parameter for assessing the risk of reactivation-related seal breach, the fault analysis seal technology (FAST), which allows for the input of a failure envelope with cohesion. Jones et al. (2002) and Dewhurst and Jones (2002) have demonstrated that fault rocks may show significant postdeformation lithification caused by cementation that results in the regaining of cohesive and, therefore, tensile strength. Thus, knowledge of the fault rock failure envelope should be incorporated into predictions of fault reactivation.

The likelihood of fault reactivation and associated seal breach can be assessed by the FAST method given the knowledge of the stress field, pore pressure, fault orientation, and the failure envelope for the fault rocks. The in-situ stress field can be determined by a variety of wellbore geomechanical techniques. Density and check-shot velocity data yield the vertical stress, borehole breakouts and drilling-induced tensile fractures yield the orientation of the horizontal stresses, leak-off and extended leak-off tests yield the minimum horizontal stress, and the maximum horizontal stress can be determined by the occurrence or nonoccurrence of breakouts and drilling-induced tensile fractures and
knowledge of rock strength (see, e.g., Bell, 1996; Moos and Zoback, 1990, for detailed discussion of these techniques). Knowledge of the fault failure envelope can be determined from laboratory testing of intact fault rocks (Handin and Jaeger, 1957; Handin, 1969; Jaeger and Cook, 1976; Dewhurst and Jones, 2002). To compensate for fault plane heterogeneity or when no strength data are available, sensitivity analysis of fault failure envelopes should also be undertaken. Fault orientation (dip and strike) is determined from depth-converted seismic interpretation. For three-dimensional (3-D) seismic data, the risk of reactivation can be mapped.

**FIGURE 2.** Geomechanical risking parameters. See text for full discussion and references. Retention capacity risks the likelihood of tensile failure of intact cap rock. Other techniques risk the reactivation of a preexisting fault, the orientation of which is specified by the dot in the 3-D Mohr circles. The position of the fault in the gray-shaded area in the 3-D Mohr circles is defined by the relative orientation of the fault and the principal stresses. CFF = Coulomb failure function.
onto the interpreted fault plane geometry in 3-D. For two-dimensional (2-D) seismic data, the dip and dip azimuth of the fault are determined from the offset between reflector terminations. A centerline point in the mapped fault polygon can then be assigned the fault dip and strike and, in turn, the risk of reactivation.

Given the requisite information, three stages to assessing reactivation risk thus exist.

1) A 3-D Mohr diagram representing the state-of-stress and failure envelope for the fault is constructed (Figure 3). The risk of reactivation of a plane of any orientation is expressed by the increase in pore pressure ($\Delta P$) required to cause its reactivation, i.e., horizontal distance on a 3-D Mohr diagram between a fault plane and the failure envelope.

2) The reactivation risk ($\Delta P$) for all planes is plotted on a polar diagram of normals to planes (Figure 3).

3) The appropriate reactivation risk ($\Delta P$) is mapped either onto the fault plane (3-D data; Figure 4) or fault polygon centerline points (2-D data).

**APPLICATION TO THE ZEMA STRUCTURE, OTWAY BASIN, SOUTH AUSTRALIA**

The Zema-1 well in the Otway Basin, South Australia, intersected a 69-m (226-ft) paleogas leg and a 15-m (49-ft) paleo-oil leg in the Lower Cretaceous Pretty Hill Formation (Lyon et al., 2005). The Zema structure has fault-dependent closure in the footwall of the Zema fault. The strike of the Zema fault varies between east–west and northwest–southwest, and it dips approximately 70° to the north (Lyon et al., 2005). Detailed analysis suggested that juxtaposition and fault deformation processes together were likely to provide an adequate seal for the observed paleocolumn (Jones et al., 2000; Lyon et al., 2005). Hence, the existing methodologies for assessing fault seal for inactive faults did not consider the observed paleocolumn, and the propensity for reactivation-related breach of the fault seal at Zema-1 was investigated.
The in-situ stress tensor in the area was constrained, as described in more detail by Jones et al. (2000), using density and check-shot log data (for vertical stress), leak-off tests and one extended leak-off test (minimum horizontal stress), and the occurrence of drilling-induced tensile fractures (maximum horizontal stress). Maximum horizontal stress orientation of 156°N was inferred from breakouts in the nearby Katnook-3 well. Pore pressures are hydrostatic. In the depth range of interest of 2500–3000 m (8200–10,000 ft), the following stress gradients apply:

- Minimum horizontal stress ($\sigma_h$) = 16.1 MPa/km
- Overburden stress ($\sigma_v$) = 22.4 MPa/km
- Maximum horizontal stress ($\sigma_{H1}$) = 28.7 MPa/km
- Pore pressure ($P$) = 9.8 MPa/km
- Maximum horizontal stress ($\sigma_{H2}$) orientation = 156°N

Unusually, core is available through a fault zone in the reservoir (Pretty Hill Formation) in the offset Banyula-1 well. The core intersected cataclasites that were tested in a standard triaxial cell with deformation features oriented at 30° to $\sigma_1$. The failure envelope derived from testing of the cataclasites, as described in more detail by Dewhurst and Jones (2002) is

$$\tau = 5.40 + 0.78\sigma'_{n}$$

where $\tau$ is the shear stress at failure, $\sigma'_{n}$ is the effective normal stress (i.e., $\sigma_n - P$), and pressures are in megapascals. We have used the failure envelope for this core in our analysis, although we recognize that the core is through the reservoir and not the seal, which may have a different rheology (see discussions in Boult et al., 2003; Dewhurst and Jones, 2003). Such potential variation in fault rock failure envelopes is a key driver for the sensitivity analysis (in very weak and strong fault rocks) described in the following section.

The entire region is covered by 2-D seismic data and a 3-D survey covers approximately half of the Zema structure. The geometry of the fault plane was determined by depth conversion and subsequent interpretation of the 2-D and 3-D seismic data over the Zema structure. Applying the FAST methodology to the above data demonstrates that significant elements of the Zema fault are optimally oriented for strike-slip reactivation in the in-situ stress field (Figure 3). The most at-risk segments are those striking approximately northwest–southeast (Figure 4). Given that juxtaposition and fault deformation processes are likely to have created an adequate seal, and that significant sections of the trap-bounding fault are optimally oriented for reactivation, we interpret that fault reactivation is a likely candidate for seal breach and, thus, the presence of the paleocolumn in the Zema-1 well.

Two pieces of additional evidence are consistent with the interpretation that fault reactivation is responsible for seal breach in the Zema-1 well. First, microstructural analysis of cataclasite samples from the fault zone in the offset Banyula-1 well indicates the presence of open fractures (Jones et al., 2000). Illites span the fractures that must be open in the subsurface. Second, a minor fault (not apparent on seismic data) is interpreted in the Laira Formation regional seal from dipmeter data in the Zema-1 well. First, microstructural analysis of cataclasite samples from the fault zone in the offset Banyula-1 well indicates the presence of open fractures (Jones et al., 2000). Illites span the fractures that must be open in the subsurface. Second, a minor fault (not apparent on seismic data) is interpreted in the Laira Formation regional seal from dipmeter data in the Zema-1 well. This minor fault is associated with a significant SP anomaly, indicating that fault zones do indeed provide a permeable zone in the regional seal (Figure 5). We are unable to determine whether this subseismic fault intersects the Zema reservoir. The main Zema fault is interpreted to cut the Zema-1 well near the base of the overlying Eumeralla Formation, and its SP effect is harder to ascertain because of the more frequent permeable sands in the Eumeralla Formation.
SENSITIVITY ANALYSIS

A sensitivity study of the results was also undertaken despite a failure envelope being available for fault rocks in the Otway Basin. This is, in part, to illustrate the application of sensitivity analysis to areas where failure envelopes are not available. Furthermore, the cataclastic zone tested in the Otway Basin is from an offset well and in the reservoir and not the cap rock. The failure envelope may change significantly along the fault plane because of changes in the rock types through which the fault cuts or because of laterally variable fluid flow and diagenetic processes along the fault. Hence, the robustness of the results was considered with respect to very weak and very strong fault rock failure envelopes.

The maximum horizontal stress is generally the least well-constrained component of the in-situ stress field. Hence, the sensitivity of the results to a range in the magnitude of maximum horizontal stress was also assessed. The most likely stress regime of the area (above) is a strike-slip regime, whereby $\sigma_{1} > \sigma_{3} > \sigma_{2}$. The robustness of the results were tested for a much lower maximum horizontal stress value equal to the vertical stress, such that the stress regime would be transitional between strike-slip and normal ($\sigma_{1} \sim \sigma_{3} > \sigma_{2}$) and also for the maximum value that maximum horizontal stress could attain, i.e., the frictional limit (Zoback and Healy, 1984) in strong rocks (coefficient of friction of 0.8). The following end-member cases were considered to assess the robustness of the assessment of reactivation risk:

- weak fault rocks ($\tau = 0.3\sigma_{1}$) and most likely stress regime above
- strong fault rocks ($\tau = 20 + \sigma_{1}$) and most likely stress regime above
- lower $\sigma_{1}$ (22.4 MPa/km, transitional strike-slip or normal fault stress regime) and failure envelope as determined from lab testing
- higher $\sigma_{1}$ (37.1 MPa/km, frictional limit for coefficient of friction of 0.8) and failure envelope as determined from lab testing

Differences in the risk of reactivation in each of the above four scenarios exist (Figure 6). However, major similarities are present in the most at-risk fault orientations that allow important generalizations to be made. A conservative approach to the sensitivity analysis is to avoid fault planes that are prone to reactivation in any single scenario and to focus on planes not prone to reactivation in any of the scenarios. Planes suitably oriented for reactivation in any single scenario strike between 100 and 210°N and dip greater than 40° (Figure 6). Planes not suitably oriented for reactivation in any of the scenarios strike between 40 and 90°N and dip greater than 60° (Figure 6).

The differences between the reactivation risk plots for each scenario essentially reflect the different mode of brittle reactivation that predominates in each case. Shear failure tends to predominate in the high maximum horizontal stress (hence, high differential stress) case and the weak fault rock case, because $(\sigma_{1} - \sigma_{3}) > 6T$. Hence, planes oriented approximately 30° to $\sigma_{1}$ and containing the $\sigma_{2}$ direction are prone to reactivation. Tensile failure is more significant in the low maximum horizontal stress (hence, low differential stress) case and the strong fault rock case, because...
Hence, planes orthogonal to $\sigma_3$ are prone to reactivation.

These differences also highlight the advantage of the FAST methodology over the Coulomb-based risking algorithms: critical pressure perturbation (CPP) and Coulomb failure function (CFF). Where differential stress is high or fault rock strength is weak, the FAST method will produce almost identical results to the CPP method. A small differential stress or strong failure envelope increases the risk of fault orientations critically oriented for tensile failure relative to those for shear failure. Therefore, CPP and CFF may overestimate the risk associated with shear failure and ignore the risk associated with fault orientations critical for tensile failure.

Significant differences exist between the $\Delta P$ values in the four scenarios. Major increases in pore pressure are required to reactivate even optimally oriented faults in the lower bound $\sigma_H$ and strong fault cases. Significant portions of the fault are at stresses beyond failure in the weak fault case. Although extreme scenarios have been used, these variations illustrate that the errors in this technique preclude it being used for predicting hydrocarbon column heights. A 1-MPa variation in $\Delta P$ is equivalent to the buoyancy pressure associated with 1 km (0.6 mi) of oil column, assuming the hydrostatic gradient is 9.8 MPa/km (~1 g cm$^{-3}$) and oil gradient 8.8 MPa/km (~0.9 g cm$^{-3}$). As shown by Figure 6, the potential errors in the methodology are greater than 1 MPa. This applies to any geomechanical methodology because of the errors inherent in estimating in-situ stresses and rock failure parameters. We believe that the value of the technique lies in its application to areas where reactivation-related breach is suspected to be an issue and in the relative risking of fault-bound prospects in such an area. The $\Delta P$ values need to be calibrated with reference to the occurrence

![Figure 6. Sensitivity analysis of the likelihood of reactivation in the Otway Basin. (A) Weak fault rocks; (B) strong fault rocks; (C) lower limit $\sigma_H$; and (D) upper limit $\sigma_H$. Plots are polar diagrams of normals to planes colored by $\Delta P$ values.](image-url)
of intact and breached columns in specific basins. For example, in the Timor Sea, ΔP values less than 10 MPa represent a significant risk of reactivation-related seal breach (Mildren et al., 2002).

DISCUSSION

The considerable evidence that fault and fracture reactivation leads to fluid redistribution has been summarized by Sibson (1992, 1994), Muir-Wood (1994), and Dewhurst et al. (1999). Sibson’s (1992) fault-valve model provides a mechanism whereby the cycling of tectonic shear stress and/or fluid pressure is linked to episodic fault instability and, in turn, episodic fluid redistribution. Cementation or hydrothermal precipitation may lead to faults resealing during periods of stability. The observed episodic discharge of hydrocarbons from overpressured compartments (e.g., Hunt, 1990) is consistent with this model. At the geological timescale, hydrocarbons clearly leak episodically and not continually up trap-bounding faults, because if leakage was continual at rates greater than charge, accumulations would not develop. In the Australian context, the presence of paleocolumns witnesses the fact that trap-bounding faults do seal over significant periods and, thus, that most trap-bounding faults are not permanently open conduits for leakage (O’Brien and Woods, 1995). The model followed herein, like Sibson’s (1992) fault-valve model, assumes that the observed episodic breaching of faults and associated fluid redistribution is associated with reactivation.

In some cases, fault rocks may be stronger than the surrounding rocks (Dewhurst and Jones, 2002; Jones et al., 2002), and hence, the risk of failure of intact cap rock must be considered as well as the risk of fault reactivation (Boult et al., 2002). Indeed, the risk of failure of intact cap rock may be greater than the risk of reactivating misoriented faults where the intact cap rock is weaker (Streit, 1999; Hillis and Nelson, 2005). To assess the risk of cap rock failure, it is simply necessary to add an intact rock failure envelope to the analysis. The risk of failure of intact cap rock is the increase in pore pressure that can be sustained prior to failure by the point on the Mohr circle closest to the failure envelope. In the case of cap rock analysis, a single value is provided for the (crest of the) prospect (as is the case with retention capacity; Figure 2), whereas the risk of fault reactivation varies with the geometry of the fault. The strength of fault rock material obtained at Banyula-1 suggests that sand-sand fault contacts are strong in the Otway Basin. The sensitivity analysis reveals the risk of fracturing to be very high when using a weak failure envelope. It is possible that the strength of the cap rock is weaker than the fault, and the generation of cap rock fractures at Zema is also a possibility.

It is necessary to consider the location of at-risk fault segments (low-ΔP zones) with respect to the trap as a whole. If segments of the fault with low ΔP are not coincident with the top of the structure, then reactivation may not lead to breaching of the entire column.

Reactivation must postdate hydrocarbon charge for it to cause seal breaching. If postcharge reactivation occurred in the geological past and within a paleostress regime that differed significantly from that of the present day, it should not be risked with reference to the in-situ stress field. The risk of reactivation may be assessed with reference to the in-situ stress field if leakage is associated with present-day geochemical anomalies such as those witnessed by marine geochemical sniffers and airborne laser fluorescence (Bishop and O’Brien, 1998) or if it is associated with faults that cut a young seabed and land surface. In the North Sea, the significance of the in-situ stress field to the assessment of fault leakage is witnessed by Heffer and Fox’s (1996) compilation indicating that nonsealing faults are strongly preferentially oriented in the in-situ maximum horizontal stress direction. Although in many cases, the in-situ stress field is appropriate, if leakage occurred in a paleostress field different to that of the present day, then that paleostress field must be applied to consider the risk of reactivation (Gartrell and Lisk, 2005).

All geomechanical methodologies for risking reactivation-related seal breach assign risk to seismically mapped faults. Hence, it is an implicit assumption that leakage associated with reactivation occurs on the seismically mapped structures or on structures with similar orientations. Structures that are not seismically imaged may be prone to reactivation and contribute to seal breach. Indeed, the subseismic fault cutting the Laire Formation regional seal in the Zema example is permeable. Hence, at the prospect scale, it is an assumption that seal-breaching fractures are parallel or subparallel to the mapped fault.

CONCLUSIONS

Analysis of cross-fault lithological juxtaposition and of deformation processes are routinely used to assess the likelihood of fault seal. However, these techniques cannot incorporate the potential for seal breach caused by fault reactivation subsequent to charge. Faults that are suitably oriented to be reactivated in the prevailing stress field provide conduits for fluid flow. The concepts of brittle failure and structural permeability provide the basis of a technique to assess whether seismically mapped faults are likely to be reactivated in the in-situ stress field and thus associated with seal breaching.

Faults may show significant cohesive strength caused by postdeformation cementation. The existing
geomechanical parameters used to assess the likelihood of reactivation-related seal breach assume that preexisting faults have no cohesive strength. Hence, we have introduced a new methodology (FAST) that allows input of a laboratory-derived fault rock failure envelope or a range of likely fault rock failure envelopes. The likelihood of reactivation is expressed by the increase in pore pressure ($\Delta P$) required to cause the fault to reactivate given the orientation in the in-situ stress field. This translates to an advantage over the Coulomb-derived geomechanical methodologies because it incorporates tensile failure in scenarios where either fault rock material is very strong or the differential stress is small. The technique can be readily modified to consider areas where failure of intact cap rock presents the key geomechanical risk.

Sensitivity studies incorporating variable fault strength parameters are required until fault strength can be mapped in detail across fault planes, possibly by relating strength to damage processes using gouge estimates. Once this has been achieved, the identification of across-fault leakage vs. along-fault leakage can be determined.

The FAST methodology was applied to the fault-bound Zema structure in the Otway Basin, South Australia. Juxtaposition and fault deformation processes indicated that the fault was likely to be sealing, but the structure was found to contain a residual hydrocarbon column. The FAST analysis indicates that segments of the fault are optimally oriented for reactivation in the in-situ stress field. Microstructural evidence of open fractures in a fault zone in the subsurface and an SP anomaly associated with a subseismic fault cutting the regional seal in the Zema-I well support the interpretation that seal breach is related to fracturing.

The FAST methodology provides a powerful tool for predrill assessment of the risk of fault reactivation-seal breach in all stress scenarios and fault strengths. However, limitations to such geomechanical techniques exist. First, they assume that reactivation occurs in the in-situ stress field as can be determined from wellbore data. Second, predrill risk can only be assigned to seismically mapped faults (and not subseismic faults). Finally, the errors associated with the techniques preclude them from being used to assess likely hydrocarbon column heights. Nonetheless, these techniques provide a powerful method for the relative ranking of fault-bound prospects in an area where reactivation-related breach presents an exploration risk.

REFERENCES CITED


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