Validation and analysis procedures for juxtaposition and membrane fault seals in oil and gas exploration

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Abstract: We propose and validate methods for risk analysis of fault-bounded hydrocarbon traps in exploration. We concentrate on cross-fault leakage and consider lateral seals due to (1) juxtaposition and (2) high capillary-entry-pressure fault rock (membrane seal). We conclude that stochastic methods for fault seal analysis are essential, due to the large number of structural and stratigraphic parameters and the uncertainties. Central to the methods proposed is a Monte Carlo simulation which models geometrical and stratigraphic uncertainty. Multiple Allan maps (fault-parallel cross-sections) are produced and analysed for juxtaposition and shale gouge ratio (SGR). For validation, known discoveries with independently observed hydrocarbon–water contacts (IHWC) have been back-analysed. We present two case studies in this paper, and an additional 40 case studies are summarized (four public domain and 36 confidential case studies). The model outputs were compared with the IHWC. Juxtaposition analysis with no SGR contribution gives the smallest error. The inclusion of any fault rock seal mechanisms (such as SGR) matches or increases predicted hydrocarbon column heights compared to juxtaposition and gives larger errors. We conclude there is no reason to include fault rock membrane seals in exploration prospect risking.

Conventional hydrocarbon reserves are trapped in permeable rocks (‘flow units’) that are bounded or enclosed by impermeable rocks or rock materials with high capillary entry pressure (‘seals’). A hydrocarbon reservoir can be thought of as a flow unit that is confined by both vertical and lateral seals. Most common traps consist of a top seal, typically a sub-horizontal and laterally extensive shale, salt or other fine-grained rock, coupled with some form of lateral seal. Once a potentially viable hydrocarbon system has been identified, the main task of exploration activity is to find potential traps with reservoirs, and then estimate their volume and particularly the level of the oil–water or gas–water contact. We refer to both oil–water and gas–water contacts as the hydrocarbon–water contact (HWC).

If the trap is a simple fold (four-way dip closure), then lateral seal is provided by folding of the top seal. For stratigraphic traps, lateral changes in the thickness of the seal facies or reservoir facies are required. In many cases, the lateral seal for hydrocarbon accumulations are provided by faults.

Many aspects need to be considered in the evaluation of lateral fault seals. In this paper we do not consider leaks or the movement of hydrocarbons upwards, downwards or parallel to strike along fault zones or damage zones. Instead, we concentrate on the problem of cross-fault flow into the rock material juxtaposed against the reservoir material across the fault.

Two distinct mechanisms for lateral fault seals that impede cross-fault flow are commonly considered. We refer to these two main classes as (1) primary juxtaposition seals and (2) secondary fault rock seals (membrane seals). This nomenclature generally follows that used in recent studies (Corona et al. 2010; Bretan 2016):

- Primary juxtaposition seals – in this seal type, a fault displaces a sealing lithology (commonly the top seal) into juxtaposition against the reservoir. The premise is that the juxtaposed material is impermeable over geological time. We refer to this seal mechanism as simply ‘primary seal’ or ‘primary juxtaposition seal’.

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Secondary fault rock seals, membrane seals or capillary seals – the premise in this seal type is that fault-zone material (fault rock) acts as a lateral seal due to fault-induced grain-size reductions, transport of fine-grained material along the fault zone, and/or subsequent chemical activity that creates a contiguous, low-permeability and high capillary-entry-pressure zone. We refer to this seal mechanism as ‘secondary seal’. A range of algorithms have been proposed for predicting membrane seal generation, fault rock capillary entry pressure and permeability. These have been comprehensively reviewed recently (Vrolijk et al. 2016), and include shale gouge ratio (SGR) and shale smear factor (SSF).

For both top and lateral seals, the competence of the seal is a key issue because seals must be effective for the thousands to millions of years required for hydrocarbons to accumulate. The seals must also remain intact until discovery and production (present day). This paper discusses fault seal processes over geological/charge timescales, rather than the issues of pressure change during production and depletion that occur over much shorter time frames.

We note that some studies claim to have presented definitive evidence that specific mechanisms for lateral fault seal have operated. Comprehensive reviews of many of these studies are available (e.g. Vrolijk et al. 2016). Ideally, it would be possible to devise tests and analysis procedures that would determine which mechanisms were responsible for lateral fault seals in specific hydrocarbon reservoirs. However, because it is not generally possible to make direct observations of leak points, spill points or the geometrical character of fault zones, or make direct measurements of fault-zone capillary entry pressure, it is difficult to draw unambiguous conclusions in most cases. However, any hydrocarbon accumulation can be analysed in at least some fashion with the benefit of existing datasets. These datasets typically include a depth structure contour map together with inferred stratigraphic and rock composition information, and various inferences or conclusions regarding porosity, permeability, seal composition and charge history.

We also note that there are two quantitative approaches used for fault seal assessment, which have been referred to as deterministic and stochastic (see James et al. 2004; Dee et al. 2007; Corona et al. 2010; and a review discussion by Vrolijk et al. 2016). The most common form that a deterministic analysis takes is the development of a single ‘best practice’ analysis case or alternative scenarios covering low, mid and high cases. A variety of studies have outlined so-called deterministic methods, perhaps starting with Allan (1989) and earlier studies, and the potential errors or uncertainties in each of the many input parameters to the analysis have been discussed (e.g. Bretan 2016). In contrast, only a few studies have adopted a stochastic approach in order to account for the uncertainties in the input data (see James et al. 2004; Corona et al. 2010). These two papers describe a forecasting ‘multi-fault method’, which has been developed at ExxonMobil. The published descriptions suggest that the multi-fault method was designed to address the fact that many hydrocarbon traps involve more than one fold structure and/or fault (Corona et al. 2010). The descriptions of the multi-fault method also state that for most cases, fault seal analysis that considers juxtaposition analysis with little or no fault membrane seal contribution is surprisingly accurate (Corona et al. 2010).

In this study we present a proposed method for stochastic analysis of lateral fault seals for hydrocarbon accumulations in the exploration phase. The main departure of our methods from those published earlier is that a Monte Carlo scheme is used to model both the geometrical and stratigraphic uncertainties through the production of stochastic/multiple 3D Allan maps. Table 1 compares the methods used for uncertainty analysis in the multi-fault method (ExxonMobil, as outlined by James et al. 2004) and in this study. Although James et al. (2004) used stochastic methods, the approach of the

| Parameter                              | Uncertainty type | This study | James et al. (2004)               |
|----------------------------------------|------------------|------------|----------------------------------|
| Crest and spill elevations             | Structural       | Monte Carlo| Deterministic                     |
| Fault length, throw, symmetry          | Structural       | Monte Carlo| Deterministic                     |
| Fault dip/dip direction                | Structural       | Monte Carlo| Deterministic                     |
| Throw at start and end of fault        | Structural       | Monte Carlo| Deterministic                     |
| Stratigraphic thicknesses              | Stratigraphic    | Monte Carlo| Deterministic                     |
| Strata for each layer                  | Stratigraphic    | Monte Carlo| Deterministic                     |
| Discrimination – reservoir and seal    | Stratigraphic    | Deterministic| Cut-off value applied to $V_{shale}$ |
| Hydrocarbon-specific gravity           | Hydrocarbon      | Monte Carlo| Not used                          |
multi-fault method seems to confine the stochastic methods to treatment of the stratigraphy (at least, as published). In contrast, the method we have employed applies a stochastic Monte Carlo treatment to both stratigraphic and geometrical uncertainties.

In this paper we validate the proposed methods using a back-testing or back-analysis technique. In a validation, an algorithm or method is tested by comparing a back-calculated value with an independently observed datum in order to determine the error. In a validation, an algorithm or method is tested by comparing a back-calculated value with an independently observed datum in order to determine the error. We assess critically the proposed methods using case studies of known hydrocarbon accumulations where drilling has provided an independently observed hydrocarbon–water contact level (IHWC). In the back-testing procedure a mathematical model of the field geometry (from seismic mapping) and stratigraphic information as would have been available in a pre-drill exploration scenario are explored using a Monte Carlo simulation. We then compare the Monte Carlo simulation model result with the IHWC. Because the IHWC is not used in the modelling, it is thus an independent datum for the validation process. The techniques we use do not employ a calibration step where the algorithms are adjusted via a constant or function in order to improve the match between the modelled output and the IHWC.

In the methods we have employed, we specifically consider lateral fault seals caused by two mechanisms. These are (a) primary juxtaposition seal and (b) secondary juxtaposition augmented by fault membrane (fault rock) seal. In order to conduct the study, a library of known hydrocarbon accumulations has been assembled and then analysed using the same procedure. In particular, we used accumulations or case studies where:

- The faults have seismically resolvable displacement – typically more than 20–25 m. In addition, each reservoir or trap must have a seismically resolvable closure with a demonstrable vertical separation between the structure crest and potential leak points.
- The top seal is thick enough to expect that it can be correlated reliably across the structure. In practice, this is usually a reasonable assumption because we are analysing a single fault block at a time. We have only considered cases where the top seals are generally thicker than the seismic resolution but, in most cases of known hydrocarbon accumulations, this is true.
- Each accumulation that is used as a case study must have an IHWC. These need to be constrained in some way, typically using drilling information, most commonly pressure data or well testing, and sometimes also using well logs. Although there is always uncertainty in the observations of the IHWC, when we compare the model outputs with the secondary seal analysis we consider the IHWC as a fixed value.

Procedure and methods

The analysis procedure employed in this study follows the procedure described initially by Allan (1989) in that fault-plane profiles (now referred to as Allan maps in common usage) are constructed. The stochastic analysis methods we use are substantially different to those published by James et al. (2004). The method we have used consists of the following steps:

1. The best quality seismic reflector that is near the reservoir of interest is used as a reference horizon. The reference horizon provides a foundation of the analysis, and the elevations of the crest, seals and flow units are measured or projected vertically relative to this surface.
2. Assuming generally conformable stratigraphy through the trap area, the intersections of the fault and the reference horizon are captured as x, y, z polylines representing the footwall and hanging wall.
3. The footwall and hanging-wall polylines are used to calculate a 3D fault displacement profile. Displacement profiles are reviewed as long sections of their 2D components (throw and heave profiles). At this point, unrecognized compound faults, relay ramps, and/or overzealously joined and over-lengthened faults are frequently discovered and corrected. Shortening or otherwise editing the fault traces is a common action at this stage.
4. A general structural geological review of the characteristics of a fault network is performed, considering the techniques mentioned by Nixon et al. (2014). Specifically, each fault’s displacement to length ratio is checked. As discussed by Schultz & Fossen (2002) and earlier by Dawers et al. (1993), the ratio of maximum displacement to total fault length scales approximately linearly. If the ratio falls well outside of typical bounds, there is good reason to question the fault interpretation.
5. For each fault, the observed throw profile is approximated using a set of second-order polynomials. The simulation of the faults in the stochastic analysis involves defining each genetic segment as a footwall polyline and distributions representing:
   (a) fault length;
   (b) maximum throw;
(c) position of maximum throw (a function of fault length);
(d) throw at the start and end of the fault (a function of maximum throw), thus allowing for fault branch lines and for segmented traps where the fault tip is not pertinent to containment;
(e) fault dip and dip azimuth.

(6) The analysis is performed on individual fault blocks. Because each fault block is considered in isolation, the automatic part of the analysis does not explicitly consider things such as backfilling where a hydrocarbon water contact (HWC) in one fault block is controlled by a leak point in an adjacent fault block (see Allan 1989 for a discussion of backfilling). Each fault block is defined by a series of leak constraints, consisting of:
(a) one or more faults;
(b) one or more ‘structural’ spill points, which we refer to as SSPs. Spill points consist of fold rollovers or elevation changes in the trap geometry that are not related to faults but which would limit the ultimate height of the hydrocarbon column. Sometimes these are referred to in common usage as lowest closing contour (LCC). Spill points are described as a distribution of elevations relative to the reference horizon.

(7) For each fault block, a simplified stratigraphy based on two rock types (seals and flow units) is defined. In the method used in this study, the discrimination between seal and flow unit is not made automatically, instead it is user-controlled, and is often done by reference to log data. Each unit is described using a gross thickness and a $V_{\text{shale}}$ content, and these parameters are assigned uncertainties using statistical distributions. We note that the $V_{\text{shale}}$ values are not used in the juxtaposition analysis. The sole purpose of the $V_{\text{shale}}$ values in the analysis methods is to calculate the SGR value (below).

(8) In some analyses, it is sensible to include a thickness variation and distribution to allow for growth faults, lateral changes in thickness and extra thickness changes across faults. This has not been done in any of the case studies presented or summarized in this paper. In some cases, special considerations need to be made for major unconformities or for channel sands. This has not been done for any of the case studies presented or summarized in this paper.

(9) As many of the distributions are poorly understood and are commonly based on small sample sizes, triangular distributions have been used in the analyses, and each distribution is described using a low, mid and high value.

(10) Using a Monte Carlo simulation engine, each of the parameters that describe the leak constraints, the stratigraphy, and the structure crests and spill points are sampled 10 000 times.

(11) In the case of stacked reservoirs, the stratigraphic thicknesses are used to derive spill points for flow units deeper and shallower than the reference horizon. In this way, the uncertainties of the SSP, crests and stratigraphic thicknesses are reasonably propagated through the model.

(12) For each realization, Allan maps are created as a set of 3D polynomials. The across-fault juxtapositions of flow units are calculated through the use of these polynomials:
(a) for each flow-unit to flow-unit juxtaposition, the elevation of the structurally highest juxtaposition leak point is calculated;
(b) for each juxtaposition polygon, SGR is expressed as a function of the hanging-wall and footwall polynomials, and thus is explicitly a function of the throw, the thickness of each layer and $V_{\text{shale}}$. The SGR function is converted into an across-fault pressure difference (AFPD) 4D function (Yielding 2002). In this analysis, a Monte Carlo randomized average hydrocarbon specific gravity (SG) is used rather than a phase-segregated SG as it allows for uncertainty treatment of dual hydrocarbon phases scenarios. The AFPD function is converted to a ‘hydrocarbon down to’ function following the method described by Yielding (2002). Finally, the ‘hydrocarbon down to’ function is searched to find the structurally shallowest leak point for each juxtaposition.

(13) Within each of the 10 000 realizations, a flow unit in a fault block can have a number of juxtapositions across one or more faults. These are tabulated for both the primary juxtaposition seal analysis and the secondary juxtaposition plus SGR seal analysis. The structurally shallowest leak point for each fault block (FLP) is recorded for each Monte Carlo realization, both for the primary seal analysis (recorded as FLP1) and for the secondary seal analyses (recorded as FLP2). For fault blocks with more than one bounding fault, the identity of the fault controlling the leak point is also recorded as summary information.
For each of the 10 000 realizations, using two scenarios, the FLP1 and FLP2 are compared with the Monte-Carlo-sampled structural spill point (SSP) to determine whether the controlling factor is fault related or, alternatively, SSP related. Using the trap crest elevation, each realization is checked for its capacity to trap a column. This provides the modelled hydrocarbon water contact (MHWC) levels, which we refer to as MHWC1 for the primary seal analysis and MHWC2 for the secondary seal analysis.

In exploration forecasts, the 10 000 realizations for primary seal and secondary seal are collated to generate distributions of MHWC1 and MHWC2. The MHWC are used with the structural crest to derive distributions of modelled column height.

To provide more clarity on the methods we have used, Table 1 compares the treatment of uncertainties in the ExxonMobil multi-fault technique (James et al. 2004) with the methods used in this study.

Case studies

Two case studies have been used to illustrate selected aspects of the analysis method. The data for the case studies are fully in the public domain. The data are available in either published papers or from government data repositories, as outlined with each case study. In these case studies, a simple depth map and basic log data or stratigraphic interpretations were available. Although these may seem to be cursory data, the results from these case studies illustrate the methods well, and also show that, even with simple datasets, reasonable analyses can be performed.

In order to validate the methods proposed in this paper, each case study has been modelled. In a validation, an algorithm or method is tested by comparing a back-calculated value with an independently observed datum in order to determine the error. Using the 10 000 Monte Carlo simulations, a distribution of validation errors can be generated for each case study.

Ling Gu, Malay Basin

The data for this case study were published in 2004 (James et al. 2004). A map in that publication (reproduced in Fig. 1) shows clearly the faults, structure crest and a likely spill point (SSP). The published map has a missing contour, but the required details for an analysis can be inferred. Dee et al. (2007) also discuss Ling Gu. Fault traces and the elevations of the hanging-wall and footwall intersections of the A-Sand with the fault traces were digitized directly from the map (Fig. 2). In the Ling Gu case, primary juxtaposition seal provides both a more conservative and a more accurate estimate of the IHWC than a secondary seal.

Corallina Field, offshore NW Australia

The data for this case study are freely available from the online data repository which is administered and maintained by Geoscience Australia (the Commonwealth of Australia geoscience research and resources agency). The data that were used.
include a discovery report submitted by Woodside Petroleum, and also the well logs from the discovery well (Corallina-1) and the second well (Corallina-2). Although many wells are available (Corallina-1–Corallina-7), we concentrated on the first two vertical wells because the other wells are highly deviated through the critical part of the seal stratigraphy. When drilled, the IHWC was found to be substantially shallower than expected. In the discovery report, it was postulated that one of the bounding faults could be leaking. Corallina is amongst a number of fields where palaeohydrocarbon columns have been reported, and it was suggested that the shallower IHWC is due to a range of fault reactivation phenomena (Castillo et al. 2000; de Ruig et al. 2000; Gartrell et al. 2005). Allan maps were not included in these studies, and it was stated that the fault displacement was less than the thickness of the top seal and that no thief zones have been reported (de Ruig et al. 2000; Langhi et al. 2010). In de Ruig et al. (2000), a fault reactivation leak point 56 m deeper that the IHWC was identified.

The map (from the Corallina-2 well completion report) has 20 m contours, and shows two faults: one on the north side and one on the south side (Fig. 5). The crest of the structure can be located on the map at about −3130 m. The independently observed OWC (IHWC), based on pressure testing, was initially thought to be at −3215 m, but this was later revised based on petrophysics and further testing to −3219 m, as described in the Corallina-2 well completion report. The fill to spill level or lowest closing contour (SSP) is approximately −3330 m, as observed from the map.

The map (Fig. 5) was used to digitize the top Laminaria Formation intersections with the North and South faults. The North Fault was divided into two sections, because there is a distinct and clear branch line (labelled in Fig. 5). To the west of this branch line the North Fault has a throw of 300–350 m, and to the east of the branch line the throw is 560–620 m. The North Fault throw profiles are shown in Figure 6. The South Fault was divided into two sections, based on the throw profile (Fig. 7). We used two sections (which are likely to be the same fault) because we can then achieve a very good match between the observed throw profiles and the polynomial approximation (Fig. 7).

We used the logs from Corallina-1 to develop a basic stratigraphy that is described in Table 3.
A key point of our analysis was to use the observed gas logs and completion reports. In these data we found that prominent gas kick started in the Echuca Shoals Formation and/or the Darwin Formation. Although the Echuca Shoals Formation has a high gamma-ray response, it is a source rock (Palu et al. 2017). The observed prolific mud gases show that the unit is transmissive; thus, we inferred that this unit could act as a thief zone for the purposes of exploration timescale fault seal analysis. Although the Echuca Shoals Formation has a high gamma-ray count, we conclude that this may result from a high organic content rather than a high clay content. It is thought that because the Echuca has expelled hydrocarbons, it may have significant fracture transmissivity.

All four fault segments are potentially important in the analysis. Typical Allan maps are shown in Figure 8. The NE fault (with the largest throw) consistently juxtaposes the Laminaria Formation reservoir against the Hibernia and Bathurst formations (Fig. 8a), which did not show gases during drilling and were also generally logged as uniform calcilutite. We infer that this fault sealed relatively dependably because of this juxtaposition. This leaves the two segments of the South Fault and the west segment of the North Fault. All four fault segments were run using the Monte Carlo analysis techniques (Table 4). The results suggest that the main juxtapositions of importance are the reservoir when juxtaposed against the Echuca Shoals thief zone, particularly along the central part of the South Fault (Fig. 8b).

The model results are shown as distributions in Figure 9. For the primary seal analysis, 98% of the realizations have shallowest juxtapositions on the west segment of the South Fault, and 2% have shallowest juxtapositions on the east segment of the South Fault. These juxtapositions control the MHWC1. With the secondary seal analysis, 100% of the realizations indicate fill to spill (MHWC2 is controlled by the SSP or spill level).
Table 2. Summary of the uncertainty distributions used for the Ling Gu analysis

| Gu Ling uncertainty distributions | Low       | Most likely | High    | Distribution type |
|-----------------------------------|-----------|-------------|---------|-------------------|
| **General**                       |           |             |         |                   |
| Crest (elevation)                 | −1308.0   |             |         | Flat              |
| Spill (elevation)                 | −1425.0   |             |         | Flat              |
| Top seal thickness (m)            | 270.0     | 300.0       | 330.0   | Triangular        |
| V$_{shale}$ thickness (%)         | 50.0      | 70.0        | 90.0    | Triangular        |
| A-Sand thickness (m)              | 15.0      | 40.0        | 62.0    | Triangular        |
| V$_{shale}$ shale (%)             | 144.0     | 160.0       | 176.0   | Triangular        |
| Base seal thickness (m)           | 58.0      | 69.0        | 80.0    | Triangular        |
| **Fault A**                       |           |             |         |                   |
| Dip (°)                           |           |             |         | Flat              |
| Dip azimuth (°)                   |           |             |         | Flat              |
| Length (m)                        | 5495.6    | 5505.6      | 5515.6  | Triangular        |
| Maximum throw (m)                 | 9.6       | 33.6        | 63.6    | Triangular        |
| Position maximum throw (%)        | 57.0      | 61.0        | 65.0    | Triangular        |
| Throw start (m)                   | 0.0       | 5.0         | 10.0    | Triangular        |
| Throw end (m)                     | 0.0       | 5.0         | 10.0    | Triangular        |
| **Fault B**                       |           |             |         |                   |
| Dip (°)                           |           | 65.0        |         | Flat              |
| Dip azimuth (°)                   |           | 243.3       |         | Flat              |
| Length (m)                        | 7305.1    | 7315.1      | 7325.1  | Triangular        |
| Maximum throw (m)                 | 35.4      | 65.4        | 95.4    | Triangular        |
| Position maximum throw (%)        | 49.5      | 49.6        | 49.7    | Triangular        |
| Throw start (m)                   | 0.0       | 22.5        | 68.1    | Triangular        |
| Throw end (m)                     | 0.0       | 10.0        | 45.9    | Triangular        |

Fig. 3. Ling Gu Allan Map – Fault A. Following the convention used by Allan (1989), we present the Allan map view direction from the west towards the footwall block. The Monte Carlo analysis estimates the crest of the reservoir to reservoir juxtaposition (and, hence, MHWC1 for a primary juxtaposition analysis) as −1381 ± 11 m. This is within a few metres of the independently observed IHWC (from drilling) at −1385 m.
For Corallina, the mean error between the MHWC1 and IHWC is 21.7 m, with a standard deviation of 12.0 m. The mean error between the MHWC2 and IHWC is 111.0 m, with a standard deviation of 8.2 m. The fault reactivation leak-point error proposed in earlier studies lies intermediate between the MHWC1 and MHWC2 errors, at approximately 57 m (de Ruig et al. 2000). In the Corallina case, primary juxtaposition seal provides both a more conservative and a more accurate estimate of the IHWC than a secondary seal. We also note again that any fault membrane seal mechanism, when included in a fault seal analysis, will give the same or deeper MHWC than a juxtaposition-alone analysis.

General results

A summary of the validation errors from the Ling Gu and Corallina case studies, as well as four other case studies, is presented in Figure 10. The basic data for the additional case studies that are shown in Figure 10 (West Seahorse, Griffin, Minerva and Dory) are available from government data repositories or published papers, and are fully within the public domain. Minerva is located in the Otway Basin in the state of Victoria (Southern Australia). West Seahorse is located in the Gippsland Basin in the State of Victoria (Southern Australia). The information for both Minerva and West Seahorse is available from Earth Resources Victoria (Victorian state...
Fig. 6. Fault profiles for the North Fault, Corallina. (a) Hanging-wall and footwall profiles; these are the elevations of the intersections between the North Fault and the Top Laminaria Formation surface. The fault branch line is a natural place to divide the north bounding fault into two segments. (b) Throw profile for the east segment of the North Fault. (c) Throw profile for the west segment of the North Fault.

Fig. 7. Fault profiles for the South Fault, Corallina. (a) Hanging-wall and footwall profiles; these are the elevations of the intersections between the South Fault and the Top Laminaria Formation surface. The South Fault is reasonably divided into two segments and the throw for the segments is shown in parts (b) & (c).
Table 3. Summary of the stratigraphy used for the Corallina analysis

| Stratigraphy | Type   | Thickness (m) | V_{Shale} (%) |
|--------------|--------|---------------|---------------|
|              |        | Min. | Mean  | Max. | Min. | Mean  | Max. |
| Prion TO     | Seal   | 400  | 500   | 600  | 5    | 15    | 30   |
| Hibernia TE  | Seal   | 300  | 400   | 500  | 5    | 15    | 30   |
| Bathurst T   | Seal   | 85   | 115   | 140  | 10   | 35    | 50   |
| Jamieson KC  | Seal   | 75   | 85    | 95   | 10   | 40    | 70   |
| Darwin NKA   | Seal   | 8    | 10    | 12   | 10   | 40    | 70   |
| Echuca KA    | Thief  | 20   | 25    | 35   | 20   | 40    | 60   |
| Flamingo–Frigate | Seal | 190  | 215   | 220  | 50   | 70    | 90   |
| Laminária JO | Reservoir | 110  | 130   | 150  | 10   | 20    | 30   |

Fig. 8. Selected Allan maps for the Corallina Field. (a) Allan map for the eastern part of the North Fault, which has the largest recorded throw (c. 600 m). The throw coupled with the inferred stratigraphy suggests that the reservoir will be consistently juxtaposed against the Hibernia and Bathurst Formations, and is thus expected to seal. (b) Allan map for the west segment of the South Fault. The model shows that this fault will consistently control the MHWC1 because of juxtaposition of the reservoir against the Echuca Formation, which has been modelled as a thief zone.
|                  | Low          | Most likely | High        | Distribution type |
|------------------|--------------|-------------|-------------|-------------------|
| Crest (elevation)| −3130        | −3370       | −3360       | Flat              |
| Spill (elevation)| −338         | −3370       | −3360       | Triangular        |
| **South Fault West** |             |             |             |                   |
| Dip (°)          | 70           | Flat        | Flat        |                   |
| Dip azimuth (°)  | 175          | Flat        | Flat        |                   |
| Length (m)       | 2519         | 2529        | 2539        | Triangular        |
| Maximum throw (m)| 261.9        | 291.9       | 322         | Triangular        |
| Position maximum throw (%) | 80          | 83          | 85          | Triangular        |
| Throw at start (%) | 0           | Flat        | Flat        |                   |
| Throw at end (%)  | 95           | 98          | 100         | Triangular        |
| **South Fault East** |           |             |             |                   |
| Dip (°)          | 67           | Flat        | Flat        |                   |
| Dip azimuth (°)  | 207          | Flat        | Flat        |                   |
| Length (m)       | 3338         | 3348        | 3358        | Triangular        |
| Maximum throw (m)| 343          | 373         | 403         | Triangular        |
| Position maximum throw (%) | 50          | 51          | 52          | Triangular        |
| Throw at start (%) | 75           | 80          | 85          | Flat              |
| Throw at end (%)  | 80           | 88          | 97          | Triangular        |
| **North Fault West** |           |             |             |                   |
| Dip (°)          | 71           | Flat        | Flat        |                   |
| Dip azimuth (°)  | 4            | Flat        | Flat        |                   |
| Length (m)       | 3128         | 3138        | 3148        | Triangular        |
| Maximum throw (m)| 443          | 473         | 403         | Triangular        |
| Position maximum throw (%) | 50          | 51          | 52          | Triangular        |
| Throw at start (%) | 75           | 80          | 85          | Flat              |
| Throw at end (%)  | 80           | 88          | 97          | Triangular        |
| **North Fault East** |           |             |             |                   |
| Dip (°)          | 67           | Flat        | Flat        |                   |
| Dip azimuth (°)  | 205          | Flat        | Flat        |                   |
| Length (m)       | 3338         | 3348        | 3358        | Triangular        |
| Maximum throw (m)| 343          | 373         | 403         | Triangular        |
| Position maximum throw (%) | 50          | 51          | 52          | Triangular        |
| Throw at start (%) | 75           | 80          | 85          | Flat              |
| Throw at end (%)  | 80           | 88          | 97          | Triangular        |

Fig. 9. Modelled hydrocarbon–water contacts (MHWC) for Corallina shown as distributions. Two distributions are shown: (a) assuming a primary seal mechanism and (b) assuming a secondary juxtaposition plus SGR seal mechanism.
and/or from Geoscience Australia (Commonwealth Government of Australia). Dory is located in the Southern North Sea. The information is available from the UK Government as a relinquishment report filed by Centrica in 2013. The Griffin dataset was published by Brincat et al. (2006).

In addition to the six case studies presented, more than 87 additional hydrocarbon accumulations from 36 additional fields have been analysed by the authors (Fig. 11). The full details of these accumulations cannot be published because of confidentiality restrictions. For all of these accumulations, juxtaposition analysis results in a small validation error.

Given the nature of the primary juxtaposition analysis and of the inferences inherent in all secondary membrane seal algorithms (SGR and all others), it is clear that juxtaposition analysis alone will always predict the same or shallower HWC than any combined juxtaposition plus membrane seal analysis. We have chosen and tested only one of the many published algorithms for secondary fault seal analysis: the SGR algorithm from Yielding (2002). We note that the choice of the membrane

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**Fig. 10.** Summary of the validation error for the case studies presented in this study (Ling Gu and Corallina) and for four additional case studies for which the location and field name can be shared, and for which the data are publically available (Dory, Minerva, Wet Seahorse and Griffin). (a) Table showing the summary errors. Note that there are four stacked reservoirs in the West Seahorse Field. In the Dory example analysis there is no SGR contribution, so only a primary juxtaposition result is shown (the primary and secondary analysis produce the same results). The error for the Dory example is also very small because of the geometrical configuration of the reservoir layer and the faults. (b) Plot summary of the errors and the standard deviation of the errors.

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**Fig. 11.** Cumulative error distribution plot for primary juxtaposition analyses. These consist of analyses of 36 confidential fields and the six fields shown as case studies in Figure 10a. Because some of the fields include stacked reservoirs, this figure summarizes a total of 87 accumulations from the confidential case studies and nine accumulations from the case studies presented in Figure 10a. Error is illustrated as a binned histogram (blue); the orange line represents the probability density function.
seal algorithm will not change the juxtaposition error. Moreover, the difference in the errors that result from different membrane seal algorithms will be very small in comparison to the large errors that result from the use of any membrane seal algorithms when the basic assumptions inherent in these algorithms are not appropriate or correct. Because our stochastic/probabilistic primary juxtaposition analyses produce a closer match to the IHWC than the secondary or combined juxtaposition plus SGR analyses, we suggest that there is no reason to include membrane seal mechanisms in fault seal analysis conducted for exploration purposes. This conclusion is consistent with a number of earlier studies, including Allan (1989), James et al. (2004), Corona et al. (2010) and Davis & Corona (2014).

We also note that our results and analysis do not disprove the presence or function of numerous types of lateral fault seals. For example, our analyses do not disprove the existence of hydrocarbon accumulations where the column height is limited by the strength of the cap rock. These mechanisms are certainly possible, but consideration of these mechanisms does not appear to be necessary to explain the large number of hydrocarbon accumulations that we have examined.

**Discussion**

In this section we discuss three aspects of lateral fault seals:

1. The seal quality required to produce useful seals over geological timescales.
2. The geometrical understanding of fault-zone evolution and the potential implications for fault seals.
3. Deterministic v. stochastic strategies for analysis.

In order to provide perspective, we present a short thought experiment that considers flow rates and timing.

- A leak rate of 10 barrels/year would be equivalent to an average leak rate for the juxtaposition area of $c. 0.0001$ barrels/year/m$^2$ (or $4.4$ litre/hectare/year or $16$ ml/m$^2$/a$^{-1}$).

Based on these rates, sizes and times, we suggest that it is difficult to expect a membrane seal to act as a hydrocarbon trap where the seal is required to maintain integrity over millions of years. In particular, we guess that it would be unusual for a perfectly intact capillary seal to be generated by tectonic processes. It is interesting to compare with the human timescale problem of domestic waste disposal. The standards for municipal waste isolation in Victoria, Australia, specify a need for a $30$–$50$ year confinement of leachate, across a five-layer system including a $1$ m-thick, $1 \times 10^{-9}$ hydraulic conductivity, clay layer on top of a carefully prepared foundation and covered with a specially designed $1.5$–$3$ mm geomembrane and geotextile cover (EPA Victoria 2015). The single thick clay layer has to be laid as three separate layers, each rolled flat to ensure consistent compaction. The design specifically refers to a pressure difference of $0.5$ m head ($0.5$ psi pressure difference). The permissible leakage rate of $10$ l/hectare/year is comparable to the leakage rate required to drain our hypothetical oilfield. Despite the possible augmentation in oil and gas seals that may result from two-phase flow considerations or from capillary seal (Watts 1987), the fact still remains that a very low average leak rate is sufficient to drain hydrocarbon fields over geological timescales, and the geological seal systems are far weaker than specifically engineered solutions.

For membrane seals, we suggest that there is an incorrect assumption in the most commonly used algorithms that are proposed for fault membrane seals. The assumption is that the fine-grained gouge material will be continuous and uniform along the fault zone. For more discussion of these issues, we direct readers to the review studies by Childs et al. (2009) and Vrolijk et al. (2016), which focus on the issue dominantly from the oil and gas perspective. In addition to these studies, there are numerous studies of outcrop analogues which frequently document examples of very irregular gouge-zone thicknesses measured along the slip direction of outcrop-scale faults (e.g. Lehner & Pilar 1997; Fordford et al. 1998; van der Zee & Urai 2005). In particular, the work on the Airport Road Faults in Miri Sarawak show that there is very little lateral continuity in fault rock when measured along strike (Sosio de Rosa et al. 2018). There are also many relevant studies published in the structural geology and seismological realm that address the character and evolution of fault gouge zones (e.g. Robertson 1983; Scholz 1987; Hull 1988; Blenkinsop 1989; Power & Tullis 1995; Brodsky et al. 2011). These studies,
although conducted in allied research areas, are clearly relevant to discussions of fault membrane seals, and may provide the terminology and insights needed to improve the relatively common description in the oil and gas realm of ‘holes’ in the membrane seals (e.g. see Vrolijk et al. 2016, sections 3.1.3 and 3.1.4 for a discussion of holes).

Finally, we have drawn attention to the difference between ‘deterministic’ and ‘stochastic’ fault seal analysis methods (as have earlier studies: e.g. James et al. 2004; Corona et al. 2010; Vrolijk et al. 2016). We suggest that the relatively large and numerous uncertainties can be analysed most appropriately with a stochastic technique that addresses both stratigraphic and geometrical uncertainties. Because it is not possible to make \textit{in situ} observations of fault zones, leak points, spill points or the geometrical character of fault zones, it is impossible to deterministically infer which of many possible mechanisms cause faults to seal or leak. Rather than focusing on whether our results prove or disprove certain mechanisms, we have focused on a pragmatic solution to the exploration problem, namely: how can we predict the HWC most accurately? We suggest that rather than using complex process and algorithms to solve an uncertain problem, it is better to conduct fault juxtaposition analysis using a stochastic technique, and that an essential first step in any analysis is the creation of the classic Allan maps.

Conclusions

Back-analysis of over 96 hydrocarbon accumulations from 42 fields demonstrates that using stochastic modelling provides a close approximation to the independently observed hydrocarbon water contact levels (IHWC) using the kind of information that is commonly available in exploration. We find that when fault uncertainty is modelled, the use of a simple primary juxtaposition mechanism provides more conservative and more accurate forecasts of IHWC than secondary analyses which combine juxtaposition analysis with shale gouge ratio (SGR). Our analyses clearly suggest that the addition of SGR and thus any other membrane fault seal mechanisms to juxtaposition analyses can erroneously increase predicted hydrocarbon column height, and in many cases will make proposed exploration prospects look more attractive than warranted. The case studies indicate that primary juxtaposition seal analysis provides a significantly smaller error than secondary juxtaposition augmented with an SGR/membrane seal. Thus, there is no reason to use membrane seal analyses in exploration, unless there is a sound validation. We also conclude that a stochastic or probabilistic analysis is essential for successful hydrocarbon column forecasting because of the number of input parameters, their interrelationships and the large uncertainties that are inherent in the data.

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Appendix A: Glossary and terminology

| Abbreviation | Definition |
|--------------|------------|
| AFPD | Across-fault pressure difference function, this is part of the SGR calculation |
| FLP | Fault leak point, this is a modelled leak across a fault at a reservoir to reservoir or a reservoir to thief juxtaposition |
| FLP1 | Fault leak point 1, this is a shallowest fault leak point for a given fault block, modelled using the primary juxtaposition analysis (with no membrane seal or SGR contribution) |
FLP2 Fault leak point 2, this is a shallower fault leak point for a given fault block, modelled using the secondary analysis, which considers juxtaposition augmented with a fault membrane seal contribution. In this study the fault membrane seal contribution used is SGR.

GWC Gas–water contact

HWC Hydrocarbon–water contact, includes both oil–water (OWC) and gas–water contacts (GWC)

IHWC Independently observed hydrocarbon–water contact (typically observed from pressure data or drill-log information). We refer to this datum as independent because it is used in the validation and is not used in the model methodology

LCC Lowest closing contour

MHW Modelled hydrocarbon–water contact, in this paper this acronym is used to refer to the results of the modelling rather than the observations and the IHWC

MHW1 Modelled hydrocarbon–water contact 1 derived from a primary juxtaposition analysis with no contribution from membrane seal mechanisms

MHW2 Modelled hydrocarbon–water contact 2 derived from a secondary juxtaposition plus SGR/membrane seal analysis

OWC Oil–water contact

SG Specific gravity

SGR Shale gouge ratio

SSP Structural spill point, this refers to a level where the trap or field will leak as a result of folded or topographical variations in the top seal that are not specifically related to faults. Similar or equivalent concepts are LCC and the fill to spill level

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