Seismic interpretation of the eastern Gippsland Basin with application to fault seal analysis in carbon dioxide storage leads

by

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CHAPTER 5—CARBON DIOXIDE STORAGE LEADS

5.1 Introduction
The structural interpretation of the study area (Chapter 3), together with a depth conversion of seismic horizons (Chapter 4), forms the foundation from which to identify CO$_2$ storage leads (CO$_2$SL). Further, a screening process using appropriate selection criteria are also required to ascertain the study area’s CO$_2$ storage potential and, associated migration pathways.

Previous studies addressing CO$_2$ storage and petroleum migration exist. For example, two pertinent basin-scale CO$_2$ migration pathways, the Northern Gas and Southern Oil Field routes, have been identified in the western part of the Gippsland Basin using the depth-structure map of the top Latrobe Unconformity (Root et al., 2004; Root, 2005). The routes were established on the basis of CO$_2$ injection in the Central Deep, away from petroleum-producing fields; thus, allowing time for fields to reach the end of their production cycle before migrating CO$_2$ reaches them. One case study involved the Kingfish Field located updip of the Central Deep; there, reservoir simulations of stratigraphic–depositional-based geomodels were carried out to ascertain CO$_2$ migration rates and pathways. En route storage dominated the volumetric capacity (Gibson-Poole et al., 2006a; Gibson-Poole et al., 2008a). The onshore part of the Gippsland Basin was also assessed and ranked according to basin-scale screening criteria (i.e. not at the scale of a CO$_2$SL); onshore, the Latrobe Group interval was found to be reduced in comparison to its offshore equivalent resulting in limited CO$_2$ storage options (Gibson-Poole et al., 2008b). More recently, hydrocarbon-based fluid-flow modelling was carried out to identify migration routes and explain the observed trap fill-and-spill scenarios (O’Brien et al., 2008). The modelling showed that hydrocarbons migrate from the Central Deep towards the flanks of the basin; and a good match was found between predicted and known petroleum accumulations.

To-date, CO$_2$ storage research is dominated by basin-scale desktop studies with most regional assessments being underpinned using 2-D based seismic interpretations. Overall, CO$_2$ storage research at the scale of a CO$_2$SL has not been underpinned by 3-D seismic interpretations prior to this study; thereby, providing a research opportunity.

The primary objective in Chapter 5 is to identify CO$_2$SLs and screen them according to structure-based criteria newly introduced in this study; many CO$_2$SLs are located within fault-block complexes that encapsulate fault-throw families (major, minor), but that have varying degrees of fault complexity (i.e. fault network, branching faults, hinge and fault zones). The secondary objective is to evaluate, in parallel, the structure-based screening criteria used to ascertain their potential in geotechnical assessments of other basins.
5.2 Terminology

The CO$_2$ storage terms introduced in this chapter form part of the terminology and structure-based criteria newly introduced for the purpose of geotechnically assessing a basin’s CO$_2$ storage potential.

**Carbon dioxide storage lead (CO$_2$SL):** The petroleum industry uses the term ‘lead’ in the context of a potential drilling target where the closure is only partially proven (three-way dip closure). When the closure is believed proven, it is called a prospect (four-way dip closure). Here, the term CO$_2$SL is defined as ‘a potential geological storage site for CO$_2$ where trap closure is only partially proven and, where other screening criteria have not been considered as yet (e.g. injectivity, seal).

**Carbon dioxide storage prospect (CO$_2$SP):** If other screening criteria are included, then the term ‘carbon dioxide storage prospect’ is used.

**CO$_2$ storage site:** This is a CO$_2$SP where further assessments (e.g. economic modelling, reservoir simulation, risk and uncertainty analysis) have been carried out. This definition is in line with the description introduced by Bradshaw et al. (2002) and Bradshaw et al. (2004) and, as previously introduced in Chapter 1 (Figure 1.1). A CO$_2$ storage site is considered conceptual where assessments have been carried out at a subregional scale, but where limitations and uncertainty exist as a result of loose data control.

**Flow-path distance:** The term refers to the fluid-flow pathway at the scale of a CO$_2$SL/CO$_2$SP (Figure 5.1); it is defined as the maximum in-line distance from a location downdip of a structural trap (possibly a CO$_2$ injection well/injector) and, extending to the crest of the structure. In reality, migrating CO$_2$ would take a convoluted pathway through a reservoir, so that its true flow-path distance will always be longer than its direct in-line distance. Also implied is that the CO$_2$ would almost certainly migrate within the greater closure of the trap to eventually pool within the culmination.

**Flow-path height:** The term refers to the maximum in-line height from a location downdip of a structural trap and, extending to the crest of the structure (Figure 5.1).

The benefit of estimating and adopting the use of the terms flow-path distance and height is that they allow a comparison of CO$_2$SLs. The inline flow-path distance and height extend outside of the lowest closing contour (LCC) within a trap; the benefit being the access to any additional storage volume from residual and dissolution trapping. Positioning of CO$_2$ injectors downdip then becomes important to maximise the trapping potential of CO$_2$ within the CO$_2$SL (Figure 5.1).
Sweep area: The term refers to the maximum area inside and, in part, outside of the LCC that can potentially be swept by CO₂ injected within one reservoir interval for CO₂ injectors located at the maximum downdip extent of an updip trap (Figure 5.1).

Sweep volume: The term refers to the maximum volume inside and, in part, outside of the LCC that can potentially be swept by CO₂ injected in multiple reservoir intervals for CO₂ injectors located at the maximum downdip extent of an updip trap (i.e. similar definition to sweep area; Figure 5.1).

Figure 5.1. Conceptual representation of a CO₂SL—portrayal of the criteria used to screen CO₂SLs. The maximum flow-path distance and flow-path height are calculated from the maximum downdip location and, extending to the crest of the structure. The potential sweep area is calculated from the lowest contour within the sublead.

The estimated sweep area and volume will always be greater than the area and rock volume that will be swept by migrating CO₂, the reason being that vertical and lateral baffles present ultimately impede fluid flow and limit CO₂ storage. Faults acting as baffles to CO₂ fluid-flow bring to the forefront the concept of baffle density; the latter can be conceptualised in a cross-sectional or volume sense. Figure 5.1 illustrates major, minor and subseismic faults that could act as baffles to fluid flow.
Establishing the fault network across fault-block complexes is the forerunner to establishing the fractal distribution of fault length and slip/throw within a study area, the latter demonstrated in the studies of Villemin et al. (1995) and Bailey et al. (2005).

5.3 Methodology

Workflow steps used to identify and screen CO₂ SLs are outlined as follows.

(i) Six reservoir intervals are considered for this study (i.e. GBeaSS, LHalSS1, LHalSS2, UHalSS1, UHalSS2 and UHalSS3; see Figure 3.4 for definition). The presence of reservoir quality as well as its distribution has been simplified by: (1) estimating them from average palaeoenvironments interpreted (Figures 5.2–5.3); and, (2) estimating the sand-to-shale ratios based on a 100 API cut-off of the GR log. Areas of nondeposition and/or erosion are identified from seismic data.

(ii) Seals are described in this study on a seal interval basis where the interval is represented by a subgroup or formation. No reference to individual top seals is made nor is mercury injection capillary pressure (MICP) analysis used to ascertain the integrity of individual seals. The effectiveness of top seals is proven by the large column heights retained in petroleum accumulations (ESSO Australia Ltd, 1988). However, faults are discussed in conjunction with seal intervals to understand the potential fault-seal issues related to fault traps. Intra-seal interval faults are differentiated from faults that propagate up from the main Halibut Subgroup and its reservoir intervals.

(iii) Closures were identified on the depth structure map of each seismic horizon for the Latrobe Group (SeahSS, ILHalS, LHalS, IUHalS, MackMS and LatrSS)—closures were not identified at the OtwaMS and LongSS horizons, as respective stratigraphic intervals are considered too deep for CO₂ storage.

(iv) Closures were overlain to determine the vertical stacking arrangements; closures in some areas were grouped, and then given an ID number, incorporating the prefix CO₂ SL. Subleads were then defined by distinguishing varying structural gradients and closures.

(v) The maximum inline flow-path height, flow-path distance and sweep area are estimated for each closure and at each seismic horizon that relate to each reservoir interval of interest.

(vi) A study subarea was defined from the top three screened CO₂ SLs.

(vii) The seismic variance attribute was regenerated within the study subarea using a low operator length (L = 44 ms); thus, enabling the presence of any smaller-scale faults to be detected.
The CO$_2$SLs were then screened according to a set of structure-based criteria, the rational for the latter, previously discussed (Chapter 1). These structure-based criteria are described below.

- **Depth to the reservoir interval**: Shallow reservoir depths are favoured due to the lower drilling cost, higher chance of porosity preservation, as well as higher seismic resolution being anticipated.

- **The fault network across fault-block complexes**: A lower fault count is favoured because of a lower risk of pressure build-up in a reservoir being used for CO$_2$ injection—the fault network is estimated qualitatively by plotting the strike along the fault trace on stereonets.

- **Structural hinge-lines and/or areas of high structural gradient**: If present, hingelines and/or areas of high structural gradient are more likely to have fractured reservoir overlying them, potentially leading to a higher density fault network across fault-block complexes, leading to an increased likelihood of trap breach and/or compartmentalisation.

- **Flow-path distance**: Longer flow-path distances are favoured over shorter ones, as they offer a greater capacity and flexibility for CO$_2$ storage.

- **Flow-path height**: Similar comments apply to flow-path heights as above.

- **Sweep area**: Similar comments apply to sweep areas as above.

- **Structural trap**: A structural trap, if present at the up dip culmination of the CO$_2$SL, will facilitate upgrading the CO$_2$SL to a CO$_2$SP and, potentially, to a CO$_2$ storage site.

### 5.4 Results

#### 5.4.1 Interpretation of reservoir intervals

**GBeaSS interval**

The GBeaSS interval (Chimaeras Fm) has been intersected in Volador-1 where the sand-to-shale ratio is estimated at 0.2 (Figure 5.2a), the interval is thin to absent over the Northern Strzelecki Terrace. Elsewhere, the sand-to-shale ratio ranges from 0.2 at Stonefish-1 to 1 at Judith-1. A coastal plain palaeoenvironment interspersed with marine incursions is interpreted (Partridge, 1999).
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Figure 5.2. Palaeoenvironment maps and sand-to-shale ratios—Latrobe Group (reservoir intervals).
(a) GBeaSS interval (c. 89–75.5 Ma). (b) LHalSS1 interval (c. 75.5–68.2 Ma). (c) LHalSS2 interval (c. 68.2–64.8 Ma). (d) UHalSS1 interval (c. 64.8–53.3 Ma). See Chapter 2 for definition of formations and, refer to Figure 3.4 for definition of intervals.

Note 1: Red numbers - sand-to-shale ratios estimated from logs (see Figure 5.3 for description).
Note 2: Palaeoenvironment maps redrawn after Partridge (1999; figs 4.07-4.09, 4.10, 4.11-4.12, 4.13-4.14 for parts a to d, respectively).
Figure 5.3. Palaeoenvironment maps and sand-to-shale ratios—Halibut and Cobia Sgps (reservoir-seal intervals).

(a) UHalSS2 interval (c. 53.3–51.5 Ma). (b) UHalSS3 interval (c. 51.5–49.5 Ma). (c) CobiSS interval (c. 49.5–32 Ma). See Chapter 2 for definition of formations (Fm). See Chapter 2 for definition of formations and, refer to Figure 3.4 for definition of intervals.
LHalSS1 and LHalSS2 intervals

The LHalSS1 interval (Volador Formation) has been intersected in Pilotfish-1 and Volador-1 (central–southern part of the study area) where the sand-to-shale ratio is estimated at 0.4 and 0.1, respectively (Figure 5.2b). Sand-to-shale ratios can be high (e.g. 0.9 in Kipper-1; 0.7 in Tuna-4), but are low (0.1–0.3) in the eastern part of the study area. The presence of the LHalSS1 interval cannot be confirmed over the Northern Strzelecki Terrace. A coastal plain palaeoenvironment, interspersed with marine incursions in the southeastern part of the study area is interpreted (Partridge, 1999).

The LHalSS2 interval (Volador Fm) is less deeply buried than the LHalSS1 interval—a few wells have penetrated into it. Sand-to-shale ratios range up to 1 in the Halibut Field (Figure 5.2c). In the southern part of the study area, the interval is in large missing as a result of uplift and erosion, although two remnant areas exist at Pilotfish-1 and Volador-1, where the sand-to-shale ratios are estimated at 0.6 and 0.4, respectively. Over the broad terrace area, the sand-to-shale ratio ranges up to 0.7 at Tuna-2. The presence of the LHalSS2 interval cannot be confirmed over the Northern Strzelecki Terrace—as indicated from seismic onlap, it is either thin to absent. A coastal plain palaeoenvironment interspersed with marine incursions is interpreted (Partridge, 1999). However, the LHalSS2 interval in the southeastern part of the study area is dominated by marine siliciclastics deposited on a continental shelf.

UHalSS1 and UHalSS2 intervals

The UHalSS1 and UHalSS2 intervals (Kingfish or Mackerel Formations) have been the primary reservoir intervals targeted for petroleum exploration and, as such, these are well sampled (Figures 5.2d and 5.3a). The sand-to-shale ratio estimates are high, at 1.0 and 0.7 in the Halibut and Tuna Fields, respectively. The reservoir intervals are thin to absent over the Northern Strzelecki Terrace. The palaeoenvironment is the same as for the LHalSS2 interval except that open marine conditions now prevail in the southeastern part of the study area where, due to low sedimentation rates, a condensed section developed (Figure 5.3a).

5.4.2 Interpretation of seal intervals

Halibut Subgroup

All CO₂SLs interpreted at the LHalSS horizon (discussed in Section 5.4.3) are probably sealed by the Kate Shale; considered a local seal in the study area. Any CO₂SLs interpreted at other levels (SeahSS, ILHalS and IUHalS horizons) incorporate intraformational seals that have been
demonstrated to be effective seals by their association with oil trapped in the intra-Latrobe Group, for example at the Flounder Field (ESSO Australia Ltd, 1988; Younes, 1988).

**Cobia Subgroup—Flounder Formation**

The CO₂SLs interpreted at the MackMS horizon (discussed in Section 5.4.3) are overlain by seals of the Flounder Formation and/or Cobia Subgroup. Seals within both the Flounder Formation and Cobia Subgroup are considered, for the most part, local. Similarly, reservoirs and/or thief zones may be locally present within these intervals (Gibson-Poole et al., 2006a).

The Flounder Formation has a thin (< 50 m) to condensed section, except in the Tuna-Flounder Channel where the sediment fill is up to 450 m (see Chapter 3). Faults arrest at the Mackerel Unconformity; itself equivalent to the base of the Tuna-Flounder Channel. The dominant palaeoenvironment is a shallow marine shelf (Figure 5.3b), although subordinate marine siliciclastics and a coastal plain palaeoenvironment have been interpreted in the northwestern corner of the study area (Partridge, 1999). Sand-to-shale ratios in most wells are estimated at less than 0.3 although exceptions exist, such as at Kahawai-1, where the sand-to-shale ratio is 0.9 (Figure 5.3b). Overall, however, the basal Flounder Formation lithology is postulated through sequence stratigraphic studies to act as a local reservoir unit, whilst the upper part as a seal unit (Ross, 2004).

The Cobia Subgroup is thin (i.e. < 20 m) to absent in places. Thicker sections exist at Blackback-1 (101 m), Blackback-3 (57 m), Marlin-4 (67 m), Patricia-1 (44 m), Rockling-1 (48 m), Turrum-1 (113 m) and Wrasse-1 (155 m). Glauconitic-rich marine palaeoenvironments dominate (Partridge, 1999) although the Burong Formation in the Baleen wells is an exception; here, sandy units of unknown origin have been intersected (Figure 5.3c). Generally, the sand-to-shale ratios are less than 0.1, and the Cobia Subgroup lithology is interpreted to reflect a seal unit.

**Seaspray Group**

CO₂SLs interpreted at the Latrobe Unconformity (LatrSS horizon, discussed in Section 5.4.3) are sealed by the marly-to-shaly Swordfish Formation. The Swordfish Formation is considered, for the most part, to act as a regional to local seal but may be ineffective where the interval pinches out. The Swordfish Formation is overlain by the carbonate-dominated wedge (up to 2.7 km in thickness) that forms the rest of the Seaspray Group (see Chapter 3).

The seal interval incorporated as the Swordfish Formation is relatively unfaulted, although fault clusters occur in the SworSS interval, in the central northwest parts of the study area (Figure 5.4; see Chapter 3). A second fault cluster overlies petroleum fields located in the southwestern corner of
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Figure 5.4. Isopach map—SwoRSS interval.
See Appendix 1 (Table A1.1) for well names.
the study area (Cobia, Fortescue, Halibut and Mackerel Fields). The latter fault cluster coincides with and/or overlies the edges of the Marlin Channel (see Chapter 3).

The regional seal represented by the Seaspray Group and seismically by the combined CongSS-to-UWhitSS intervals, is up to 2.2 km thick (see Chapter 3: Figure 3.25). The combined interval has fault clusters present in the CongSS interval (see Chapter 3) and is transected by a few faults. Overall, the Seaspray Group interval is considered a highly competent regional seal.

Evidence provided in this study suggests that the majority of fault tips arrest at the Mackerel Unconformity (MackMS horizon); thereby, reducing the chance of fluid escape via faults into the local seal intervals that incorporate thief zones (i.e. Flounder Fm and Cobia Subgroup). Lastly, the CO₂SLs described in the next section share a common feature in that any CO₂ would ultimately pool under the regional seal represented by the Seaspray Group.

5.4.3 Interpretation of CO₂SLs

Twelve CO₂SLs have been identified in the study area and these are described systematically in the following sections according to the screening criteria introduced in the methodology section. Depth structure maps for seismic horizons SeahSS to LatrSS (Figures 5.5–5.10) are used to compliment the description of structure associated with 11 of the CO₂SLs. One exception is the facies-based CO₂SL-12 where an isopach map is used to compliment the description (Figure 5.11). The screening criteria, including average flow-path distance, flow-path height and sweep area, have been estimated from the depth structure maps above and, these are represented in histograms for all subleads (Figures 5.13–5.15).

CO₂SL-1

CO₂SL-1 incorporates Grunter-1 and Stonefish-1—subleads include 1a–1f (Figures 5.5–5.9); traps interpreted include rollover, fault, subcrop and faulted subcrop traps. The dominant fault strike is WNW–ESE-trending with a minimal fault network interpreted across fault-block complexes (see stereonet in Figure 5.12). All faults are normal and dip SSW at ~ 60–70°. The rerun of the seismic variance attribute at a low aperture gate (L = 44 ms) provided faint evidence of minor bifurcations with short trace-lengths less than 100 m abutting major faults. All fault tips arrest at the Mackerel Unconformity (MackMS horizon).

Grunter-1 and Stonefish-1 reached TD in the LHalSS2 interval; thereby, adequately sampling potential reservoirs within the upper Halibut Subgroup. However, the UHalSS2 interval is, in part, absent as observed from the subcrop edge (Figure 5.8). Seal interval thicknesses, represented by
Figure 5.5. CO2 SLs at the Seahorse Unconformity—depth-structure map of the SeahSS horizon. See Appendix 1 (Table A1.1) for well names.
Figure 5.6. CO₂ SLs at the intra-lower Halibut unconformity—depth structure map of the ILHalS horizon. See Appendix 1 (Table A1.1) for well names.
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Figure 5.7. CO$_2$SLs at the lower Halibut unconformity—depth structure map of the LHalSS horizon.
See Appendix 1 (Table A1.1) for well names.
Figure 5.8. CO$_2$SLs at the intra-upper Halibut unconformity—depth structure map of the IUHalS horizon. See Appendix 1 (Table A1.1) for well names.
Figure 5.9. CO₂ SLs at the Mackerel Unconformity—depth structure map of the MackMS horizon. See Appendix 1 (Table A1.1) for well names.
Figure 5.10. CO₂ SLs at the Latrobe Unconformity—depth structure map of the LatrSS horizon.
See Appendix 1 (Table A1.1) for well names.
Figure 5.11. CO$_2$SL-12—isopach map of the Flounder Formation and Cobia Subgroup (seal intervals).
See Appendix 1 (Table A1.1) for well names. Sediment feeder channels are identified from seismic slices of the variance attribute.
Figure 5.12. Location of CO₂ SLs—structural elements and fault strike.
Fault strike are portrayed on a combined stereographic projection–rose diagram. See Figure 3.12 for definition of fault families identified by different coloured faults in Figure 5.12.
the Flounder Formation, Cobia Subgroup and Swordfish Formation sections, are 36/73, 0/1 and 87/60 m in Stonefish-1 and Grunter-1, respectively. The seal intervals are thin to absent in places so that the integrity of traps may be compromised (e.g. Stonefish-1 was a dry well). The seismic-based isopach of the Swordfish Formation is less than 80 m thick within the extent of the lead (Figure 5.4), consistent with well-based thickness estimates. The bearing of hypothetical CO₂ migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO₂ SL-1 ranges from 300° to 020°N; flow-paths mostly subparallel the fault-strike trend. Flow-path distances range from 1.9 to 5.9 km (Figure 5.13), flow-path heights from 50–420 m (Figure 5.14) and, sweep areas from 1–20 km² (Figure 5.15).

**CO₂ SL-2**

CO₂ SL-2 incorporates the Tuna and West Tuna Fields, Batfish-1 and East Pilchard-1—subleads include 2a–2d (Figures 5.5–5.10). Traps interpreted include rollover, fault and subcrop traps, all present within two fault-block complexes that trend both NW–SE and WNW–ESE (Figure 5.12). The northern fault-block complex has the Tuna-1 and Tuna-3 wells at its structural crest. This fault-block complex is bounded to the north by the Rosedale Fault (F55, see Figure 3.12a) and fault array A4 and, to the south by faults F18 and F122. The western edge of this fault-block complex has the West Tuna Field at its structural crest where it is bounded by reverse fault F165. The southern fault-block complex has Batfish-1 at its structural crest and, is bounded to the north and south by faults F6 and F8, respectively (see Figure 3.12a).

The dominant fault strike is WNW–ESE to NW–SE-trending with a minimal fault network interpreted across fault-block complexes (Figure 5.12). Exceptions to the dominant fault strike are the NE-SW-trending reverse faults (F91 and F165) previously discussed in Chapter 3 (see stereonet in Figure 3.12d). Faults are dominantly normal mode and dip both SSW and NNE at ~ 60–70°. The rerun of the seismic variance attribute at a low aperture gate (L = 44 ms) provided faint evidence of minor bifurcations with short trace-lengths less than 100 m abutting major faults. Most fault tips arrest at the Mackerel Unconformity (MackMS horizon), but a few do arrest stratigraphically higher at the Latrobe Unconformity (LatrSS horizon).

Wells of the Tuna and West Tuna Fields were not consistently drilled to a particular reservoir interval. Wells reached TD as deep as the EmpeSS interval; thereby, sampling all of the Latrobe Group reservoir intervals. The seal intervals represented by the Flounder and Swordfish Formation sections are 0–257 m and 12 m thick, respectively; the Cobia Subgroup is absent. The bearing of hypothetical CO₂ migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of
CO₂SL-2 ranges from 310° to 330°N. This bearing subparallels the dominant WNW–ESE fault-block trend; an exception is the flow path at sublead 2c, which is bi-directional, 330° and 050°N. Flow-path distances range from 3.6 to 13.4 km (Figure 5.13), flow-path heights from 200–1,000 m (Figure 5.14) and, sweep areas from 2–25 km² (Figure 5.15).

**CO₂SL-3**

CO₂SL-3 incorporates the Kipper Field—subleads include 3a–3c (Figures 5.5–5.9). Fault traps dominate this lead with faults trending NW–SE to WNW–ESE and, a minimal fault network interpreted across fault-block complexes (see stereonet in Figure 5.12). All major faults are normal mode and dip both SSW at ~ 60°–70° and NNE at ~ 50°–60°. Most faults arrest at the Mackerel Unconformity (MackMS horizon) although a few propagate to the Latrobe Unconformity (LatrSS horizon, see Chapter 3). As compared to fault-block complexes to the south, seismic amplitude anomalies have been interpreted and found to be more prevalent in the UHalSS1–UHalSS2 intervals; these anomalies may reflect fractured reservoir intervals.

Kipper-1 and Kipper-2 reached TD in the Golden Beach Subgroup; thereby, sampling all the reservoir intervals of the Halibut Subgroup. The seal intervals represented by the Flounder Formation and Cobia Subgroup sections are 23 and 5–17 m thick, respectively. The Swordfish Formation section is less than 50 m thick as estimated from the seismic isopach (Figure 5.4). The bearing of hypothetical CO₂ migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO₂SL-3 is estimated at 330°N. Flow-path distances range from 3.2 to 4.7 km (Figure 5.13), flow-path heights from 250–475 m (Figure 5.14) and, sweep areas from 3–6 km² (Figure 5.15).

**CO₂SL-4**

CO₂SL-4 encompasses the Flounder Field—subleads include 4a–4e (Figures 5.5–5.10). Trap types include fault traps at depth that amalgamate to form a faulted subcrop at shallower levels. Subcrop traps are also present. Fault blocks trend WNW–ESE, and faults dip both to the NNE and SSW (see stereonet in Figure 5.12). The trend of the structure at the deep OtwaMS horizon is more E–W; however, this is below the reservoir interval of interest. The east Flounder fault family (arrays A8–9) dominates the Flounder Field structure; faults are interpreted as forming part of a low-offset strike-slip fault system (see Chapter 3). This strike-slip fault system offsets major reverse faults (F11, F132 and F192) that trend NE–SW (see stereonet in Figure 5.12). Overall, a minimal fault network is interpreted across fault-block complexes. All faults arrest at the Mackerel Unconformity (MackMS
horizon) and, these do not appear to have been reactivated so that the top seal is expected to be effective.

Wells Flounder-1 to Flounder-6 reached TD in the LHalSS2 interval; thereby, adequately sampling reservoirs of the upper Halibut Subgroup. The thickness of seal intervals represented by the Flounder and Swordfish Formation sections range from 182 to 330 m and 13–35 m, respectively. The Flounder Formation is uncharacteristically thick (Figure 5.11) as CO2SL-4 is located at the southern extremity of the Tuna-Flounder Channel. However, Cobia Subgroup seals are absent.

The bearing of hypothetical CO2 migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of sublead 4a ranges from 290° ± 10°N; essentially subparallel to the fault-block trend. However, the bearing of the flow-path at sublead 4b is bi-directional (290° and 010°N), as is the case for sublead 4e (110° and 240°N). Flow-path distances range from 2.8 to 6.9 km (Figure 5.13), flow-path heights from 100–750 m (Figure 5.14) and sweep areas from 1–63 km² (Figure 5.15). Flow-path heights across the Flounder Field can be large, as a result of steep structural gradients present on the southern flank of the field (Figure 5.6).

CO2SL-5
CO2SL-5 encompasses the East Halibut, Halibut, Terraglin and Trumpeter Fields—subleads include 5a–5b (Figures 5.5–5.7). Traps interpreted include fault and subcrop traps. The dominant fault strike is NW–SE-trending, fault planes dip both SSW and NNE with no fault network evident across fault-block complexes (see stereonet in Figure 5.12). Deep-seated NW–SE-trending faults arrest within the Longtom and Golden Beach Subgroups while other faults arrest at the Mackerel Unconformity (Mack horizon).

Terraglin-1 and East Halibut-1 reached TD in the LHalSS2 interval; thereby, sampling the reservoirs of the upper Halibut Subgroup. The thickness of seal intervals represented by the Cobia Subgroup and Swordfish Formation sections are 4 and 205 m, respectively; the Flounder Formation is absent. The bearing of hypothetical CO2 migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO2SL-5 is ~ 090°N. Flow-path distances range from 3.1 to 7 km (Figure 5.13), flow-path heights from 300–525 m (Figure 5.14) and, sweep areas from 4–12 km² (Figure 5.15).

CO2SL-6
CO2SL-6 encompasses Morwong-1 and Angelfish-1—subleads include 6a–6b (Figures 5.5–5.9). Fault traps and faulted subcrops are present within WNW–ESE-trending fault blocks where fault planes dip to the SSW (see stereonet in Figure 5.12). These major normal faults arrest at the
Mackerel Unconformity (MackMS horizon). Morwong-1 and Angelfish-1 reached TD within the UHalsS1 interval. The Swordfish Formation is the only seal interval developed (up to 24 m); the Flounder Formation and Cobia Subgroup are absent. The bearing of hypothetical CO2 migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO2SL-6 is 290° to 010°N. Flow-path distances range from 2.1–9 km (Figure 5.13), flow-path heights from 50–600 m (Figure 5.14) and, sweep areas from 1–21 km² (Figure 5.15).

**CO2SL-7**

CO2SL-7 encompasses the Fortescue, Halibut, Cobia and Mackerel Fields, Rockling-1 and Smiler-1—subleads include 7a–7g (Figures 5.5–5.10). Trap types present include subcrop, faulted subcrop and rollover traps. The subleads are located within WNW–ESE to NW–SE-trending fault-bounded structures where most faults dip NE to NNE (see stereonet in Figure 5.12). No fault network is evident across fault-block complexes. The faults are normal and arrest at the Mackerel Unconformity (MackMS horizon). On balance of the evidence, most faults have not been reactivated so that the top seal is expected to be intact. However, fault F47 does propagate past the Latrobe Unconformity (LatrSS horizon), so localised reactivation may exist; unless this offset is reflecting differential compaction and/or drape (see Chapter 3). Fault F47 is one of a few faults that may reflect post-Early Eocene reactivation.

All stratigraphic sections are thicker in the eastern Central Deep and consequently the deeper reservoir intervals have not been sampled. The thickness of seal intervals represented by the Flounder Formation, Cobia Subgroup and Swordfish Formation range from 2 to 44 m, 0–41 m and 195–278 m, respectively. The bearing of hypothetical CO2 migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO2SL-7 is 120° ± 020°N. Flow-path distances range from 2.5 to 14.3 km (Figure 5.13), flow-path heights from 100–850 m (Figure 5.14) and, sweep areas from 2–62 km² (Figure 5.15).

**CO2SL-8**

CO2SL-8 encompasses Gummy-1, Pilotfish-1 and Volador-1—subleads include 8a–8c (Figures 5.5–5.7 and 5.9–5.10). Trap types interpreted include subcrops and rollovers. Although no significant faults have been interpreted, faults are more difficult to detect in this area because of the depth-of-burial of the reservoir interval. Moreover, sublead 8a extends beyond the 3-D seismic grid, which limits the mapping of the closure.

Volador-1 and Gummy-1 reached TD in the Golden Beach Subgroup; thereby, sampling several of the deep reservoir intervals. However, reservoir intervals overlying the ILHals horizon are absent.
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due to uplift and erosion (see Chapter 3). No subleads exist post the ILHalS horizon (Figures 5.5–5.8). The seal intervals represented by the Flounder and Swordfish Formations are up to 82 m and 123 m thick, respectively; the Cobia Subgroup is absent. The bearing of hypothetical CO₂ migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO₂SL-8 varies, being bi-directional (160° and 210°N) because of alternate structural gradients present at the SeahSS and ILHalS horizons. Flow-path distances range from 2.4 to 4.4 km (Figure 5.13), flow-path heights from 50–625 m (Figure 5.14) and, sweep areas from 2–8 km² (Figure 5.15). Unfortunately, the subleads cannot be reliably proven up because of an absence of 3-D seismic data and depth-of-burial that limits the seismic resolution.

CO₂SL-9

CO₂SL-9 encompasses the Longtom Field, Admiral-1 and Judith-1—subleads include 9a–9d (Figures 5.5–5.9). The Latrobe Group consistently thins across the RFS and trap types are dominantly stratigraphic pinchouts that overly the Northern Strzelecki Terrace. However, most traps also rely on a fault component (Figure 5.12), especially those located over or adjacent to the SRFZ. The fault-strike distribution in the RFS is unclustered (see stereonet in Figure 5.12) and was previously described (see Chapter 3).

Longtom-1 to -3 and Admiral-1 sampled the reservoir intervals of the Latrobe Group. The seal intervals represented by the Flounder Formation, Cobia Subgroup and Swordfish Formation are up to 14, 19 and 133 m thick, respectively. The bearing of hypothetical CO₂ migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO₂SL-9 is 0° ± 010°N. Flow-path distances range from 2.6 to 7.4 km (Figure 5.13), flow-path heights from 200–1,050 m (Figure 5.14) and, sweep areas from 1–34 km² (Figure 5.15). However, subleads 9a and 9c are poorly constrained as the structure partially extends outside the 3-D seismic grid (Figures 5.5–5.9).

CO₂SL-10

CO₂SL-10 encompasses the Turrum and Marlin Fields—subleads include 10a–10b (Figures 5.5–5.10). Traps include subcrops interpreted within two fault blocks bounded by two NW–SE-trending faults and, mostly dipping SW at 60°–80° (see stereonet in Figure 5.12). All fault tips arrest at the Mackerel Unconformity (MackMS horizon).

Turrum-1, -3 and -4 and Marlin-4 reached TD in the LHalSS2 interval; thereby, sampling the upper Halibut Subgroup reservoir intervals. Seal intervals represented by the Flounder Formation, Cobia Subgroup and Swordfish Formation are up to 59, 113 and 422 m thick, respectively. The bearing of hypothetical CO₂ migration flow-paths from a injector located arbitrarily downdip anywhere along the
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Figure 5.13. Flow-path distances pertaining to subleads in the study area—horizons SeahSS–LatrSS. 
Av. = average. Stdev = standard deviation.

Note 1: flow-path distance is estimated using depth structure maps (Figures 5.5 - 5.10).
Note 2: flow-path distance not estimated for closures straddling the edge of the seismic 3-D grid.
Note 3: flow-path distance not estimated for intra-channel lead CO,SL-12.
Figure 5.14. Flow-path heights pertaining to subleads in the study area—horizons SeahSS–LatrSS.

Av. — average. Stdev — standard deviation.
Figure 5.15. Average sweep areas pertaining to subleads in the study area—horizons SeahSS–LatrSS.

Note 1: sweep area is estimated using depth structure maps (Figures 5.5 - 5.10).
Note 2: sweep area not estimated for closures straddling the edge of the seismic 3-D grid.
Note 3: sweep area for intra-channel lead (CO,SL-12): sublead 12a - 153 km², sublead 12b - 38 km².

Av.—average. Stdev—standard deviation.
edges of CO₂SL-10 is 320° ± 30° N. Flow-path distances range from 1.8 to 7.8 km (Figure 5.13), flow-path heights from 200–1,000 m (Figure 5.14) and, sweep areas from 2–17 km² (Figure 5.15). However, the structure of both subleads is poorly constrained as it partially extends outside the 3-D seismic grid.

CO₂SL-11

CO₂SL-11 encompasses Grayling-1—subleads include 11a–11b (Figures 5.5–5.7). Trap types interpreted include faulted subcrops; faults strike WNW–ESE and dip mostly to the SSW at 50°–70° (see stereonet in Figure 5.12). All fault tips arrest at the Mackerel Unconformity (MackMS horizon).

No reservoir or seal information is available from Grayling-1. The seal interval, represented by the combined Flounder Formation, Cobia Subgroup and Swordfish Formation, is less than 50 m thick; as estimated from a seismic-derived isopach (Figure 5.11). The bearing of hypothetical CO₂ migration flow-paths from a injector located arbitrarily downdip anywhere along the edges of CO₂SL-11 ranges from 300° to 350° N. Flow-path distances range from 1.8 to 4 km (Figure 5.13), flow-path heights from 75–350 m (Figure 5.14) and, sweep areas from 1–4 km² (Figure 5.15). However, both subleads are poorly constrained as the structure partially extends outside the 3-D seismic grid.

CO₂SL-12

CO₂SL-12 encompasses the West Tuna and Tuna Fields at the northwestern edge and the Flounder Field at the southeastern edge—subleads include 12a–12b (Figure 5.11). The dominant trap type within the Tuna-Flounder and Marlin Channels is stratigraphic. Low-relief rollovers may exist but cannot be confirmed without sequence stratigraphic work being undertaken. A few lineaments, that could potentially represent faults, have been interpreted within the channel. However, the lineaments are interpreted as being stratigraphic rather than structural in nature based on differing variance-attribute signatures. Further, the existence of intrachannel stratigraphic traps is established at the Tuna Field where oil has been recovered in such features (Thomas et al., 2003). However, the cut and fill nature of the intrachannel reservoirs, as demonstrated from a sequence stratigraphic study (Ross, 2004), suggests that significant compartmentalisation can be expected. There, nine cut and fill sequences have been interpreted—the lithology of the upper six sequences has a greater capacity for sealing, while the lithology of the basal three sequences has a greater reservoir potential. In this Ph.D. study, sediment feeder channels are clearly visible on seismic variance slices (Figure 5.11), and it is inferred that these provided sediment to the multilobe channel fill. Depth to the reservoir section ranges from 3.5 km at the base of the channel, to 1.45 km at its top; this depth range is within acceptable depths for preservation of porosity. Although volumetric capacity for CO₂
storage is high, the probable heterogeneities of the reservoir (cut and fill) could make CO₂ injection problematic. Surface areas for subleads 12a and 12b are estimated at 153 and 38 km², respectively (Figure 5.15). The flow-path distance and flow-path height have not been estimated as a result of the cut-and-fill nature of the trap.

5.4.4 Screening of CO₂SLs and subleads

In Section 5.4.4, CO₂SLs and subleads are compared and qualitatively ranked according to the screening criteria previously outlined in Section 5.3 with results portrayed in Table 5.1.

Traps

Faulted rollovers, faulted subcrops and fault traps are dominant at the SeahSS, ILHalS and LHalSS horizons, although pinchouts, rollovers and subcrops are also present (Table 5.1, Figures 5.5–5.7). Further, subcrop and faulted subcrop traps dominate at the IUHalS horizon; a consequence of uplift and erosion of the respective interval (Figure 5.8). Fault traps and stratigraphic pinchout traps are present within the section overlying the Northern Strzelecki Terrace. Subcrops, faulted subcrops and fault traps dominate at the MackMS horizon, this being the most prominent unconformity in this part of the Gippsland Basin (Figure 5.9). Subcrop traps and rollovers dominate at the LatrSS horizon; few faults arrest at the Latrobe Unconformity, so fault traps are absent (Figure 5.10). Intrachannel stratigraphic traps are the last identified (Figure 5.11). Ultimately, the fault-dependant traps are favoured for fault seal analysis as they link to the study’s objectives (Table 5.1).

Depth to reservoir

The depth to any given reservoir (i.e. portrayed by depth to seismic horizons) increases from north to south across the study area (see Table 5.1 for specific depths); further descriptions follow.

(i) The CO₂SLs located fully or partially within the broad terrace area are 1–4, 6 and 10–12 (Figure 5.12). The depth to reservoir for horizons SeahSS to LatrSS ranges from 3.9 to 1.4 km (Table 5.1). The deepest seismic intervals, LHalSS1 and LHalSS2, are undrilled across some parts of the Broad Terrace; and hence the reservoir properties are subsequently poorly constrained. The depth to reservoir for intrachannel CO₂SL-12 is best inferred from the MackMS and LatrSS horizons and ranges from 2.5 to 1.4 km.

(ii) CO₂SL-5 is located on a saddle within the eastern Central Deep (Figure 5.12). The depth to reservoir for horizons SeahSS to LHalSS ranges from 4.8 to 2.8 km (Table 5.1). Depths are not given for the IUHalS horizon as the underlying UHalSS1 interval has been removed through uplift and erosion.
(iii) CO2SL-7 includes structural highs located on the southern edge of the study area. The depth to reservoir for horizons SeahSS to LatrSS ranges from 5.1 to 2.3 km (Table 5.1). Reservoir intervals deeper than the LHalSS horizon are relatively undrilled in this area, probably due to the limited porosity preservation at depth.

(iv) CO2SL-8 is located in the southeastern part of the 3-D seismic grid within the eastern Central Deep. The depth to reservoir for horizons SeahSS to LatrSS ranges from 4.7 to 2.8 km (Table 5.1). As is the case with CO2SL-5, depths are not given for the LHalSS and IUHalS horizons.

(v) CO2SL-9 is located on the Northern Strzelecki Terrace. There, the depth to reservoir for horizons SeahSS to MackMS ranges from 1.8 to 1.3 km (Table 5.1). The depth range narrows as the horizons shallow because of the sedimentary thinning and progressive onlap onto the terrace.

Flow-path distance, flow-path height and sweep area

Flow-path distances can be quite considerable, up to 14 km, but are more often less than 5 km (Table 5.1). Probable flow paths have been determined both for fault blocks that trend WNW–ESE, on the broad terrace area, as well as for large-scale subcrop traps present at the IUHalS horizon. On average, and within one standard deviation, flow-path distances range from $4.4 \pm 1.7$ km at the MackMS horizon to $5.0 \pm 3$ km at the IUHalS horizon (Figure 5.13). The average flow-path distance is higher at the LatrSS horizon ($7.4 \pm 4.2$ km). However, for this case, the low lead count may have biased the average. In places, flow paths originate from within structural deeps that have undergone inversion and were later downcut by the Tuna-Flounder and Marlin Channels (Figure 5.11).

Flow-path heights range from less than 100 m and up to 1 km (Table 5.1). On average and within one standard deviation, flow-path heights range from $0.25 \pm 0.13$ km at the IUHalS horizon to $0.41 \pm 0.23$ km at the SeahSS horizon (Figure 5.14). Average flow-path heights at the LatrSS horizon are higher ($0.55 \pm 0.14$ km); however, as for flow-path distance the low lead count may have biased the average. The sublead count decreases at the IUHalS horizon because of thinning or absence of the underlying UHalSS1 interval.

On average and within one standard deviation, sweep areas range from $6.3$ km$^2$ at the SeahSS horizon and $16.9$ km$^2$ at the Latrobe horizon (Figure 5.15). In addition, the potential sweep area within closure, ranges from less than $1$ km$^2$ and up to $32$ km$^2$; excluding outliers (Table 5.1). The outliers are subleads 4a (Figures 5.15b–c), 7c (Figure 5.15d) and 12a–b (see caption in Figure 5.15). Sublead 4a forms part of the Flounder Field lead where subleads 4a–4c are no longer separated by faults, resulting in a larger sweep area. The sweep area increases at the LHalSS and IUHalS
horizons where an increase in and size of the subcrop traps is biasing the average sweep area. Lastly, subleads 12a–12b are large scale stratigraphic traps where the sweep area is estimated at 153 and 38 km², respectively. Overall, the potential sweep area estimations vary considerably and averages can be biased by the above outliers.

**Structural complexity**

In priority order, structural complexity is defined and determined qualitatively from the fault network present across fault-block complexes, number of branch lines, fault zones and structural hinge zones present in the CO²SL. The overall structural complexity for the CO²SLs is represented in Table 5.1 (column complexity).

Broadly speaking, the stereonet plots (Figure 5.12) indicate that the fault network across fault-block complexes is reduced in all CO²SLs with the exception of CO²SL-9. However, a number of distinct faults criss-crossing the fault-block complexes, as opposed to a network of faults, were shown to be present in CO²SLs 2 and 4. The relatively reduced fault network provides some assurance that migrating CO₂ will be unimpeded by vertical baffles; thus, promoting the viability of CO₂ storage.

Fault zones were previously discussed (see Chapter 3); CO²SLs affected include 2 and 4. Also, the number of branch lines is large in CO²SLs 2 to 4 relative to other CO²SLs.

Lastly, three structural hinge zones are recognised in the study area. The first is the SRFZ that underlies CO²SL-9; here, hypothetical CO₂ migration pathways in overlying reservoirs could be affected by possible intrарeservoir fracturing, potentially because of differential subsidence and compaction across the structural hinge zone. The other two structural hinge zones correspond to the Flounder deep and Turrum deep faults, both located under the southern edge of the Flounder and Turrum Fields, respectively (described in Chapter 3). These hinge zones could affecting reservoir intervals in CO²SLs 4 and 10.

**Final screening—ranking status**

Subleads were screened, from the most to least attractive, both for their CO₂ storage potential as well as for being candidates for fault seal analysis (Chapters 6–7). The lead number broadly reflects the ensuing qualitative-based ranking of the CO²SL (Table 5.1). Table 5.1 is mostly self-explanatory; however, a few points require elaboration.

(i) A high ranking was given to subleads 2b–2c. These subleads have a high level of structural complexity but are not compartmentalised. All other ranking criteria are mostly favourable; in particular, flow-path distances are considerable, being up to 12.5 km.
(ii) A medium to high ranking was given to subleads 1a–1c, 1e–1f, 2a, 2d, 3 and 4a–4d. These subleads have a medium level of structural complexity with all other ranking parameters mostly favourable.

(iii) A medium ranking was given to subleads 4e, 5a, 6a, 7b–7c, 9b–9d and 12a–12b. Most of these subleads have a low to rarely medium structural complexity. The medium ranking reflects either the short flow-path distance (e.g. 4e), presence of closures at only some of the seismic horizon levels (e.g. 5a and 6a), excessive depth (e.g. 7b), presence of structural hinge lines and thin reservoir–seal intervals (e.g. 9b–9d) and/or, absence of faults (e.g. 12a–12b).

(iv) Subleads 1d, 5b, 6b, 7a, 7d–7g, 8a–8c, 9a, 10a–10b and 11a–11b are ranked low. The low ranking reflects the fact that the structural closure is at least partially beyond the edges of the 3-D seismic grid, and as such, cannot be demonstrated.

5.5 Discussion

5.5.1 Synthesis—traps

The study area was initially chosen on the basis on its intermediate or mid-position within the sand–shale clastic wedge of the Latrobe Group (see Chapter 1). The clastic wedge is taken here in the context of the original concept of a wedge that showed how the location of petroleum discoveries could be understood in the context of the expected reservoir and seal potential at any point within the wedge (White, 1980). Too sandy a sequence, as is found in the western part of the Gippsland Basin (Root et al., 2004; Root, 2005; Gibson-Poole et al., 2006a; Gibson-Poole et al., 2008a), could be unfavourable for CO2 storage because of the high CO2 migration rates anticipated. Too shaly a sequence, as is found in the deeper and eastern part of the basin (Bernecker et al., 2001), also incorporates thinned and tight reservoir intervals, again relatively unfavourable for CO2 storage. However, at an intermediate position within the sand–shale clastic wedge, the mid to upper Latrobe Group’s gross sand thickness is still considerable, sand-to-shale ratios variable but generally medium to high and petroleum recovery rates high, but now intraformational shales are present. A good reservoir quality, with CO2 injectivity likely to be high, are indicated from the sand-to-shale ratios and favourable palaeoenvironment settings present. This high potential reservoir injectivity, in combination with the multiple stacked intraformational shales present, should allow for significant en route trapping of migrating CO2 through residual gas, dissolution and/or stratigraphic trapping; thereby, increasing the effective CO2 storage volume potential. However, towards the west, the increased sand content in the clastic wedge, in combination with the shallowing reservoirs, present a CO2 storage challenge—Can the westward migration of CO2 be trapped updip?
<table>
<thead>
<tr>
<th>Lead, sublead</th>
<th>Trap type</th>
<th>Depth (m)/seismic horizon</th>
<th>FpD (km)</th>
<th>FpH (m)</th>
<th>FpA (°N)</th>
<th>SwA (km², acres)</th>
<th>Complexity</th>
<th>Data ctl</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1, a (Stonefish)</td>
<td>Rollover, faulted subcrop</td>
<td>3100/SeahSS–1900/MackMS</td>
<td>3.1–5.4</td>
<td>100–150</td>
<td>300–320</td>
<td>4–17 (989–4201)</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>1, b (West Stonefish)</td>
<td>Fault trap, subcrop</td>
<td>2100/IUHalS–1850/MackMS</td>
<td>2.6–2.9</td>
<td>150–250</td>
<td>320</td>
<td>6–7 (1483–1730)</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>1, c (South Stonefish)</td>
<td>Faulted subcrop, rollover</td>
<td>3300/SeahSS–1900/MackMS</td>
<td>1.9–5.2</td>
<td>50–350</td>
<td>320–350</td>
<td>3–8 (741–1477)</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>1, d (Stonefish East)</td>
<td>Rollover, subcrop</td>
<td>3200/SeahSS–2400/IHalSS</td>
<td>3.8–5.4</td>
<td>125–325</td>
<td>0–020</td>
<td>3–6 (741–1483)</td>
<td>Medium</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>1, e (Grunter)</td>
<td>Rollover, faulted subcrop</td>
<td>3500/SeahSS–1950/MackMS</td>
<td>2.8–5.9</td>
<td>100–420</td>
<td>300–320</td>
<td>2–9 (494–2224)</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>1, f (Grunter South)</td>
<td>Fault trap, subcrop</td>
<td>4000/IHalS–2000/MackMS</td>
<td>1.9–4</td>
<td>150–400</td>
<td>300–350</td>
<td>3–10 (247–4942)</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>2, b (East Pilchard)</td>
<td>Fault trap</td>
<td>2500/SeahSS–1600/MackMS</td>
<td>3.6–12.5</td>
<td>200–550</td>
<td>320</td>
<td>2–7 (494–1730)</td>
<td>High</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>2, c (West Tuna-Tuna)</td>
<td>Fault trap, subcrop, rollover</td>
<td>2900/IHalS–1400/IHalS</td>
<td>5.2–9.6</td>
<td>225–425</td>
<td>330, 050</td>
<td>6–18 (1483–4448)</td>
<td>High</td>
<td>Good</td>
<td>High</td>
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<tr>
<td>3 (Kipper)</td>
<td>Fault trap</td>
<td>2200/SeahSS–1450/MackMS</td>
<td>3.2–4.7</td>
<td>250–425</td>
<td>330–0</td>
<td>3–6 (741–1483)</td>
<td>High</td>
<td>Good</td>
<td>Med-high</td>
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<tr>
<td>4, a (Flounder North)</td>
<td>Faulted rollover</td>
<td>4100/SeahSS–2400/IHalSS</td>
<td>4.2–6.9</td>
<td>200–325</td>
<td>280–300</td>
<td>13–63 (3212–15968)</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
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<td>4, b (Flounder mid-North)</td>
<td>Faulted rollover, subcrop</td>
<td>2750/MackMS–2200/LatrSS</td>
<td>5.1–6.3</td>
<td>100–750</td>
<td>290, 010</td>
<td>2–7 (494–1730)</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>4, c (Flounder mid-South)</td>
<td>Faulted rollover</td>
<td>3700/SeahSS–2300/IHalS</td>
<td>NA⁴</td>
<td>NA⁴</td>
<td>NA⁴</td>
<td>NA⁴</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>4, d (Flounder South)</td>
<td>Faulted rollover</td>
<td>3800/SeahSS–1560/IHalSS</td>
<td>NA⁴</td>
<td>NA⁴</td>
<td>NA⁴</td>
<td>NA⁴</td>
<td>Medium</td>
<td>Good</td>
<td>Med-high</td>
</tr>
<tr>
<td>4, e (Flounder West)</td>
<td>Subcrop</td>
<td>2350/IHalS–2100/MackMS</td>
<td>2.8–3.5</td>
<td>300–400</td>
<td>110, 240</td>
<td>1–16 (247–3954)</td>
<td>Low</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>5, a (E. Halibut-Teraclin)</td>
<td>Subcrop</td>
<td>2950–2850/IHalSS</td>
<td>7</td>
<td>525</td>
<td>100</td>
<td>12 (2,965)</td>
<td>Low</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>5, b (Trumpeter)</td>
<td>Fault trap</td>
<td>4700/SeahSS–3400/IHalSS</td>
<td>3–6.1</td>
<td>300–350</td>
<td>090</td>
<td>4–6 (989–1483)</td>
<td>Low</td>
<td>Good</td>
<td>Low</td>
</tr>
<tr>
<td>6, a (Morwong)</td>
<td>Faulted subcrop</td>
<td>2050/IUHalS–1950/MackMS</td>
<td>2.1–9</td>
<td>50–600</td>
<td>280–300</td>
<td>2–21 (494–5189)</td>
<td>Medium</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>6, b (Angelfish)</td>
<td>Fault trap</td>
<td>3400/SeahSS–2400/IHalSS</td>
<td>2.4–3</td>
<td>175–300</td>
<td>310</td>
<td>1–3 (247–741)</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>7, a (Rockling-Drummer²)</td>
<td>Faulted subcrop</td>
<td>4800/SeahSS–2450/LatrSS</td>
<td>2.5–9.4</td>
<td>100–600</td>
<td>130–140</td>
<td>2–14 (494–3459)</td>
<td>High</td>
<td>Poor</td>
<td>Low</td>
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<tr>
<td>7, b (Fortescue)</td>
<td>Fault trap</td>
<td>5000–4950/SeahSS</td>
<td>3.4</td>
<td>350</td>
<td>350</td>
<td>5 (1236)</td>
<td>High</td>
<td>Good</td>
<td>Medium</td>
</tr>
</tbody>
</table>
### Table 5.1. Qualitatively-based screening of CO₂SLs and subleads.

<table>
<thead>
<tr>
<th>Lead, sublead</th>
<th>Trap type</th>
<th>Depth (m)/seismic horizon</th>
<th>FpD (km)</th>
<th>FpH (m)</th>
<th>FpA (°N)</th>
<th>SwA (km², acres)</th>
<th>Complexity</th>
<th>Data ctl</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>7, c (Halibut)</td>
<td>Subcrop, rollover</td>
<td>2450/θHalSS–2300/LatrSS</td>
<td>3.6–10</td>
<td>250–550</td>
<td>115, 280</td>
<td>10–62 (2471–15320)</td>
<td>low</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>7, d (Cobia-Mackerel²)</td>
<td>Faulted subcrop</td>
<td>4900/θSeahSS–2700/θHalSS</td>
<td>10.2–14.3</td>
<td>600–850</td>
<td>120–130</td>
<td>36–42 (9390–10378)</td>
<td>High</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>7, e (Mackerel-Smiler²)</td>
<td>Faulted subcrop, subcrop</td>
<td>4700/θSeahSS–2200/LatrSS</td>
<td>3.9–7.1</td>
<td>250–800</td>
<td>130, 200</td>
<td>5–26 (1236–6275)</td>
<td>High</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>7, f (east Smiler²)</td>
<td>Subcrop</td>
<td>4500/θSeahSS–2600/θHalSS</td>
<td>3.3–3.7</td>
<td>100–200</td>
<td>120–140</td>
<td>2–5 (494–1236)</td>
<td>High</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>7, g (West Rockling²)</td>
<td>Fault trap</td>
<td>5100/θSeahSS–5000/θHalSS</td>
<td>2.8</td>
<td>100</td>
<td>100</td>
<td>2 (494)</td>
<td>Low</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>8, a (Gummy²)</td>
<td>Subcrop</td>
<td>4600/θSeahSS–3000/θHalS</td>
<td>2.6–4.4</td>
<td>50–350</td>
<td>160</td>
<td>2–7 (494–1730)</td>
<td>Low</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>8, b (Pilotfish)</td>
<td>Rollover, subcrop</td>
<td>4700/θSeahSS–3100/θHalS</td>
<td>3.2–3.3</td>
<td>250–350</td>
<td>160, 210</td>
<td>5–8 (1236–1977)</td>
<td>Low</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>8, c (Volador)</td>
<td>Rollover, subcrop</td>
<td>4500/θSeahSS–2900/LatrSS</td>
<td>2.4–5</td>
<td>150–625</td>
<td>090–100</td>
<td>2–8 (494–1977)</td>
<td>Low</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>9, a (east Longtom²)</td>
<td>Fault trap, pinchout, subcrop</td>
<td>1800/θSeahSS–1250/MackMS</td>
<td>2.6–3.9</td>
<td>200–600</td>
<td>350–0</td>
<td>1–11 (247–2718)</td>
<td>Low</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>9, b (North Judith)</td>
<td>Pinchout, subcrop</td>
<td>1300/θHalSS–1100/θHalS</td>
<td>6.2–7.4</td>
<td>400–800</td>
<td>350</td>
<td>14–25 (3459–6178)</td>
<td>Low</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>9, c (Admiral¹)</td>
<td>Fault trap, pinchout, subcrop</td>
<td>1700/θSeahSS–1200/MackMS</td>
<td>4.6–6.5</td>
<td>425–1050</td>
<td>350–010</td>
<td>5–34 (1236–8402)</td>
<td>Low</td>
<td>Average</td>
<td>Medium</td>
</tr>
<tr>
<td>9, d (South Longtom¹)</td>
<td>Fault trap</td>
<td>1900/θSeahSS–1600/θHalS</td>
<td>3.7</td>
<td>600</td>
<td>350</td>
<td>2 (494)</td>
<td>Low</td>
<td>Average</td>
<td>Medium</td>
</tr>
<tr>
<td>10, a (Turrum²)</td>
<td>Faulted subcrop</td>
<td>3700/θSeahSS–1800/LatrSS</td>
<td>4.1–6.2</td>
<td>300–1,000</td>
<td>300–350</td>
<td>6–17 (1483–4201)</td>
<td>High</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>10, b (Marlin²)</td>
<td>Faulted subcrop</td>
<td>2600?/θSeahSS–1800/LatrSS</td>
<td>1.8–7.8</td>
<td>200–400</td>
<td>290–300</td>
<td>2–13 (494–3212)</td>
<td>High</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>11, a (Grayling²)</td>
<td>Faulted subcrop</td>
<td>2700/θSeahSS–2200/θHalS</td>
<td>1.8–4.0</td>
<td>75–350</td>
<td>340–350</td>
<td>1–2 (247–494)</td>
<td>Medium</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>11, b (North Grayling²)</td>
<td>Faulted subcrop</td>
<td>2500/θSeahSS–2200/θHalS</td>
<td>2.8–3.3</td>
<td>200–250</td>
<td>300–340</td>
<td>2–4 (494–989)</td>
<td>Medium</td>
<td>Poor</td>
<td>Low</td>
</tr>
<tr>
<td>12, a (Tuna-Flounder)</td>
<td>Intrachannel trap</td>
<td>2500/MackMS–1450/LatrSS</td>
<td>NA³</td>
<td>NA³</td>
<td>NA³</td>
<td>153 (37807)</td>
<td>Low</td>
<td>Good</td>
<td>Medium</td>
</tr>
<tr>
<td>12, b (Marlin)</td>
<td>Intrachannel trap</td>
<td>3500/MackMS–1650/LatrSS</td>
<td>NA³</td>
<td>NA³</td>
<td>NA³</td>
<td>38 (9380)</td>
<td>Low</td>
<td>Good</td>
<td>Medium</td>
</tr>
</tbody>
</table>

Column 1—Sublead 4a (wells F-3, F-5), 4b (wells F-2), 4c (wells F-1, F-6), sublead 4d (Tukari-1). ¹overlies a structural hinge line, ²structural closure extends outside of the seismic 3-D grid—only minimum estimate of SwA given. Columns 2–3—Trap types, depth to horizons SeahSS–LatrSS (see Figures 5.5–5.10). Columns 4–6—cannot be calculated precisely, ³subleads 4a and 4c–4d merge, represented as 4b, FpA—flow-path azimuth. Column 7—Sweep areas calculated from depth structure maps, rounded off to nearest integer. Column 9—data control considered poor when structural closure extends outside of the seismic 3-D grid. Column 10: Ranking parameters include depth range of reservoir interval, CO₂ flow-path distance (FpD), flow-path height (FpH), sweep area (SwA), structural complexity (i.e. fault network across fault-block complexes, branch lines, fault zones, hinge zones), data control (ctl), proximity of structural hinge lines and presence of structural closure. Green, orange, red reflects high, medium and low ranking, respectively. Med—medium.
Structural trapping of migrating CO\textsubscript{2} should be possible in fields located along the Northern Gas and Southern Oil Field regional migration routes (Root et al., 2004; Root, 2005). These regional migration routes eventually extend to the onshore and terminate adjacent to Signal Hill-1 (O’Brien et al., 2008). However, these regional migration routes have been solely determined from 2-D seismic grids, so that trapping along these routes has not been evaluated at the local scale. Only regional faults were considered in previous studies; for example, in drainage cell modelling (O’Brien et al., 2008) and in reservoir simulations (Root et al., 2004; Root, 2005)—these authors did not consider minor faults potentially present across CO\textsubscript{2} migration flow-paths. However, the fault strike plotted on stereonets demonstrate that faults do strike at obtuse angles to the dominant NW–SE fault trend so that these could provide fault traps to CO\textsubscript{2} migrating westward. Ultimately, all faults must be considered in a CO\textsubscript{2} storage assessment.

Assessments of petroleum accumulations primarily address the structural closure while assessments of CO\textsubscript{2}SLs incorporate a storage component within a potential sweep area located outside closure. Although CO\textsubscript{2}SLs and subleads have been defined at seismically interpreted horizons, CO\textsubscript{2}, in practice, would be injected into multiple reservoirs within the sedimentary section of interest, bringing to the forefront the concept of ‘sweep volume’. It is anticipated that the complex geometry of both fault and shale seal baffles will play a part in impeding CO\textsubscript{2} migration. The CO\textsubscript{2} storage volume potential of CO\textsubscript{2}SLs recognised in this study has not been evaluated. However, simplified CO\textsubscript{2} volume estimates based on near-depleted petroleum field volume estimates range from 3.2 MtCO\textsubscript{2} at the Blackback Field, to 577 MtCO\textsubscript{2} at the Marlin Field (Gibson-Poole et al., 2008a). Combining the CO\textsubscript{2} storage volume estimates for most fields in the Gippsland Basin results in a minimum CO\textsubscript{2} storage potential of 1.22 GtCO\textsubscript{2} for the study area.

Furthermore to the above, the known distribution of hydrocarbon fields (gas and oil) and the interpreted palaeo-hydrocarbon migration flow-paths can be used as a proxy for anticipating CO\textsubscript{2} flow paths. Broadly speaking, because the upper Latrobe Group is exceptionally sandy, the majority of hydrocarbons have migrated through the intraformational seals up to the top of the combined sand interval. By far the largest volumes of hydrocarbons are present in traps that subcrop the Mackerel Unconformity (ESSO Australia Ltd, 1988); however, exceptions exist. The main oil accumulation in the Flounder Field is pooled in the intra-Latrobe T-1.1 sandstone reservoir, while secondary oil is present in the deeper T8 reservoir (Hordern, 1988). The Flounder Field is sealed by a 500 m thick sequence of intra-Latrobe Group shales. Consequently, the intra-Latrobe Group faulted reservoir of the Flounder Field can be considered representative of a subcrop–fault trap combination that has
successfully trapped hydrocarbons. It follows that the potential for CO$_2$ entrapment at multiple horizons and, within fault-bound traps is both plausible and probable.

One aspect of fault-trap breach to be considered involves CO$_2$ migrating vertically via conduits subparalleling the faults into localised thief zones known to be present in the Flounder Formation and/or Cobia Subgroup. Furthermore, the Gurnard Formation (Cobia Subgroup) over the Kingfish Field has been described as being a ‘chemically immature, heterogeneous, low permeability reservoir’ (Gibson-Poole et al., 2006a). Across the study area, the reservoir versus seal characteristics of the Flounder Formation and/or Cobia Subgroup sections are variable, although the intervals are more likely to act as local seals and/or low permeability reservoir than as thief zones (Gibson-Poole et al., 2005; Gibson-Poole et al., 2008a). Ultimately, the seal characteristics restricted to a local setting requires geological modelling, subsequent to the structure-based assessments provided.

5.5.2 Synthesis—CO$_2$SLs

CO$_2$SL-1 has a significant upside storage potential because both flow-path distances and flow-path heights are considerable. However, undrilled subleads, especially sublead 1c, are also viable petroleum drilling targets. The absence of hydrocarbons in the intra-Latrobe Group T-1 sand at Grunter-1 was interpreted by Young (2007) to be due to the well being drilled off-structure, as well as, sand-on-sand windows being present across-fault. Moreover, subeconomic oil in the T-8 sand at Grunter-1 is considered the result of a more favourable sand-on-shale window present across-fault. The intra-Latrobe Group sands in Stonefish-1 are wet with only minor gas shows present in the Golden Beach Subgroup. Fault relay zones were shown to play a part in controlling the lowest known hydrocarbons at Grunter-1 (Young, 2007). Thus, the presence of oil at Grunter-1 together with the absence of hydrocarbons at Stonefish-1 suggest that juxtaposition and/or fault gouge/smear have played a part in determining the seal integrity of fault-bound traps.

Further more to the above, a velocity gradient is present within the UHalSS1–UHalSS2 intervals at CO$_2$SL-1, implying that the structural closure may be dependent on the depth conversion method used. In addition, the presence of sand-on-sand windows across-fault was demonstrated to contribute to the fault-seal risk for the UHalSS1–UHalSS2 intervals and, be more significant than for the underlying LHalSS1–LHalSS2 intervals (Young, 2007). The reason is that the younger reservoir intervals have a higher sand-to-shale ratio that translates into a higher propensity for CO$_2$ to flow across-fault. Mapping in this Ph.D. study and by Young (2007) indicates that a saddle is present west of subleads 1a–1c and 1e–1f (Figures 5.5–5.8). The presence of the saddle would provide a certain degree of ‘geographical’ containment should the subleads be considered for CO$_2$ storage.
The later point is important in the respect that the viability of CO$_2$SLs is partly contingent on demonstrating, in addition to geographical containment, adequate monitoring of a migrating CO$_2$ plume (IPCC, 2005).

Further north, at the Kipper Field (CO$_2$SL-3) reservoirs within the Golden Beach Subgroup are top-sealed by volcanics and sealed by a lacustrine shale across-fault (Sloan et al., 1992). A successful sand-on-shale window across-fault highlights the importance of demonstrating fault seal integrity in CO$_2$SL-3, as well as for other CO$_2$SLs identified in this study.

The Latrobe Group interval thins across both the SRFZ and RFZ; as a result, the associated flexure of the overlying sedimentary seal section may increase the amount of intraseal fracturing and intrareservoir compartmentalisation; thereby, downgrading CO$_2$SL-9. The higher count of Swor faults increases the likelihood of these faults being in hydraulic communication with the Latr and/or Mack faults in the underlying Latrobe Group reservoirs and, potentially, affecting trap integrity. Finally, the reliability of any seismic interpretation decreases within thin intervals due to the constructive/destructive interference effect on the seismic wavelet. The above argument indicates why the CO$_2$ storage potential of CO$_2$SL-9 is ranked as low-to-medium.

The intrachannel traps present in CO$_2$SL-12 are potentially attractive because of multiple trap types present; for example, base channel highs, subcrop, intrachannel and top porosity traps have been proposed (Ross, 2004). Nine sequences were interpreted, of which the basal three form part of a dominantly sandy aggradational system, itself overlain by a dominantly shaly marine progradational system. Facies-based compartmentalisation is expected in the intrachannel traps present in CO$_2$SL-12, but as faults have not been interpreted, the CO$_2$SL is not considered further for fault seal analysis (Chapters 6–7).

**5.6 Conclusions**

Favourable reservoir intervals for CO$_2$ injection, from most to least attractive, are those present within the upper Halibut (UHalSS1–UHalSS2), lower Halibut (LHalSS1–LHalSS2) and Golden Beach (GBeaSS) Subgroups. One reason is linked to the low-density fault network observed across fault-block complexes. For example, the reservoir intervals of the Golden Beach Subgroup are anticipated to have a higher density fault network across fault-block complexes, as interpreted from the unclustered distribution of the strike of the fault traces. In comparison, the fault network across fault-block complexes is reduced for the reservoir intervals of the upper Halibut Subgroup, as interpreted from the clustered distribution of the strike of the fault traces. A lower density fault network across
fault-block complexes can be expected to reduce the chance of pressure build up during CO₂ injection because of the reduced compartmentalisation of the reservoir system being anticipated.

The dominant trap types within the study area are subcrop, faulted subcrop and fault traps. Subordinate trap types are rollovers, pinchout edges, combined volcanic top-seal dependant fault traps and incised valley intrachannel closures. The four seal intervals represented by the Flounder Formation, Cobia Subgroup, Swordfish Formation and post-Swordfish Seaspray Group are known to adequately seal the primary petroleum-bearing reservoir intervals of the Kingfish and Mackerel Formations (UHalSS1–UHalSS2 intervals). The majority of faults have previously been shown to arrest at the Mackerel Unconformity or, equivalent base seal (Chapter 3); thereby, reducing the chance of fluid escape via these faults into reservoirs and/or thief zones locally present within the dominantly sealing intervals of the Flounder Formation and Cobia Subgroup.

Average flow-path distances and flow-path heights can be as high as 7.4 ± 4.2 km and 0.55 ± 0.14 km, respectively, depending on the seismic horizon being considered. The flow-path distances and flow-path heights are considerable, which improves the potential for storing significant volumes of CO₂ through en route migration-related residual trapping, dissolution or within local small-scale stratigraphic and structural traps. Similarly, the average potential sweep area can be as high as 16.9 ± 13 km², with the potential sweep area for the Tuna-Flounder Channel to be 153 km² (an outlier estimate). The potential sweep areas are largest for subcrop traps. Overall, CO₂SLs 1 to 3 have been ranked medium-high to high on the basis of favourable flow-path attributes, high structural complexity (i.e. high number of branch lines, low fault network across fault-block complexes, absence of structural hinge lines) in combination with other factors (i.e. depth to reservoir, and adequate data control). The three CO₂SLs are now considered to represent a study subarea where a fault seal analysis will be undertaken (Chapters 6–7).
6.1 Introduction

Twelve CO2SLs have been identified and ranked by comparing the trap type, depth to reservoir, flow-path height, flow-path distance, sweep area, fault complexity and fault network estimated across fault-block complexes (Chapter 5). A study subarea was then defined based on the top three ranked CO2SLs. Chapter 6 addresses the juxtaposition analysis across-fault and modelling of shale smear for faults present in CO2SL-1 to -3 (Figure 6.1).

In the Gippsland Basin, CO2 migration at a regional-scale is thought possible (Root et al., 2004; Gibson-Poole et al., 2008a) while fault-dependant petroleum-bearing traps have been demonstrated at a field scale, both within the Halibut Subgroup (Younes, 1988), Golden Beach Subgroup (Sloan et al., 1992) and Longtom Subgroup (Lanigan et al., 2007). It follows that uncertainty in the en route sealing potential exists so that juxtaposition analysis across-fault and modelling of shale smear undertaken on CO2SL-1 to -3 will complement the knowledge gap between the above studies. However, as previously acknowledged in other basins, well-constrained structural interpretations are first required (Dee et al., 2005).

The research objectives are to ascertain and synthesize the sensitivities associated with juxtaposition of reservoir and seal intervals across-fault as well as from modelling of shale smear; application to the greater study area and basin in general is also sought. The first workflow sequence is to build an interpretation-constrained, framework geomodel that incorporates both major and minor faults, branch lines, horizon surfaces and the respective intersection polygons (i.e. fault–horizon). The second workflow sequence includes a juxtaposition analysis that makes use of the volume of shale (V_shale) curve and key seismic surfaces. The third workflow sequence includes the modelling of shale smear across the fault plane using the SGR, the latter generated from the V_shale curve.

Fault seal analysis software attribute terms that form part of the TrapTester™ software are italicised, so as to distinguish them from similar geoscientific terms. As well, brief descriptions of possibly unfamiliar structural and fault seal analysis-related terms are provided as footnotes.

6.2 Datasets

Three well-log suites were exported from the GeoFrame™ project and imported into the TrapTester™ project (Appendix 3: Table A3.1), including:
• the natural GR log, acoustic log (DT, DTCO) and resistivity/induction logs (LLD, HART, ILD, SFL); these logs are used to interpret the unconformities/hiatus markers across the GBaSS to SworSS intervals;

• the neutron/density logs (RHOB/RHOZ, NPHI/NEUT); these logs are used to estimate the presence of any heavy minerals, organic shale and coal, and;

• the spectral GR logs (THOR/HTHO, POTA/HLLK); these logs are used to detect potassium-rich sandstones (arkoses) that may be misidentified as shale from the natural GR log.

An explanation for each well-log mnemonic is given in Appendix 3 (Table A3.1). Hydrocarbon show and porosity data were downloaded from the Geoscience Australia website (www.ga.gov.au—data and applications, energy, applications, petroleum wells applications). The cutting, core, show and porosity data that were not already in digital format were obtained from WCRs.

Figure 6.1. CO:SL-1 to -3 (study subarea)—depth structure and faults.
6.3 Methodology

6.3.1 Framework geomodel

The modelled fault surfaces and branch lines have been generated and quality-controlled as follows.

(i) The fault surfaces are gridded using the *unconstrained triangulation*\(^22\) method and a smoothing filter is applied following the gridding. Any fault-surface roughness is evident from any nonuniformity of the *tri-mesh* triangles (Figure 6.2); roughness can occur as a result of mispositioning of the fault segments. Identified mispositioned fault segments are consequently repositioned and a corrected *tri-mesh* computed. Simultaneously, fault surface attributes (*minimum\(^23\), *maximum* and *Gauss curvature*) are calculated to verify the smoothness of the fault surface.

(ii) Master and splay faults are differentiated and branch lines modelled—any tortuosity of the branch lines is manually corrected. Any nonuniformity of the seismic surfaces associated with, and potentially causing branch-line tortuosity, is taken to originate from a local mispositioning of the fault surface; the mispositioning is often minor as the fault traces were initially interpreted using seismic slices of the variance attribute, the latter deemed high-resolution.

(iii) The statistical analysis tools *fault orientation plots*\(^24\), *length–displacement cross-plots*\(^25\), *fault displacement profiles*\(^26\) and *frequency of occurrence plots*\(^27\) are used to detect any structure-related inconsistencies including intersection polygons, which are then corrected.

The generation and quality control of the modelled horizon surfaces have been completed as follows.

(i) Horizon misties are corrected to better constrain the intersection polygons (i.e. horizon-to-fault) that are subsequently generated. Various *patch*\(^28\) and *trim*\(^29\) distances were tested to

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\(^{22}\) *Unconstrained triangulation* gridding takes into account all fault segment vertices but without simultaneous smoothing.
\(^{23}\) Anomalies detected using the *minimum*, *maximum*, and *Gauss curvature* attributes are indicative of how much the fault surface deviates from being planar.
\(^{24}\) The *fault orientation* tool plots the raw and/or average azimuth of the fault trace on a combined stereographic projection–rose diagram and/or histogram.
\(^{25}\) The *length–displacement cross-plot* tool plots the maximum throw against fault-trace length.
\(^{26}\) The *fault displacement profile* tool plots the throw against fault-trace distance.
\(^{27}\) The *frequency of occurrence plot* tool plots the frequency of occurrence of a particular fault displacement (i.e. throw, heave, dip separation) against itself; the number of points varies according to the selected grid interval. A regression line can be fitted to ascertain whether the fault is fractal in nature.
\(^{28}\) The *patch distance/zone* identifies the raw data that are used when generating the horizon-to-fault surface polygons. The patch distance/zone starts from where the trim distance/zone ends (i.e. ignores data).
\(^{29}\) No raw data is included within the *trim distance/zone* when generating the horizon-to-fault surface polygons.
assess which horizon picks to include or exclude, when generating the intersection polygons. The *patch distance* was set at 900 m, which equates to greater than half the seed-line spacing of 625 m (see Figure 4.3a); the *trim distance* was set at 100 m.

(ii) Contour maps are created for the SeahSS to SworSS horizons. The horizon surface attributes *dip*, *azimuth*, *roughness*, and *Gauss curvature* are also run to detect any interpretation-related discrepancies, which are subsequently corrected. The module GridTool™ was used to produce smoothed horizon surfaces.

![Diagram 6.2: Structural terminology used in fault seal analysis.](image)

Lastly, the stratigraphic correlations and lithology are described using well cross-sections so as to convey the geological framework behind the juxtaposition analysis and, the modelling of shale smear. Specifically, the stratigraphic intervals spanning the Latrobe Group and Swordfish Formation are correlated from the available well logs. The stratigraphic intervals are then described with consideration to lithology percentages derived from the well-based log cut-offs. Reservoir and seal characteristics as well as hydrocarbon shows present in the stratigraphic intervals are also described. The combined stratigraphic correlations and lithologies estimated from the well logs provide the foundation from which to carry out the juxtaposition analysis of reservoir and seal intervals, specifically, by use of the $V_{\text{shale}}$ curve. The log-derived lithologies also aid in assigning a composition to the fault gouge, the latter used to assign rock properties in fault reactivation modelling (see Chapter 7). The cuttings aid in supporting the sand and shale-line estimated from the well-log-based cut offs, as well as in the description of lithologies in general.

30 The *roughness* attribute is the ratio between the area of a trimesh panel and its horizontal equivalent.
6.3.2 Generating $V_{\text{shale}}$ curves

The $V_{\text{shale}}$ curves were generated using the GeoFrame™ module PetroViewPlus™; only the ‘setup’ and ‘shale/porosity picks’ module components were used (see Appendix 3: Table A3.2 for parameter settings). The module WellCompositePlus™ was used to display the log curves.

Environmental corrections, other than those accounted for at the time of logging, were not applied to the wireline logs used as the necessary logging metadata has been stripped from the log headers. The environmental corrections (logging speed, centeredness of the downhole tool, mud weight) are likely to have only a marginal effect in respect to the aims of this study. A Gippsland Basin example is East Pilchard-1, where correcting for logging speed was found to have a negligible effect on results (ESSO., 2001).

The GR log is normally used to derive the shale index ($I_{\text{sh}}$) curve, which is then converted to a $V_{\text{shale}}$ curve (Dewan, 1983). The steps below describe the process followed to derive the $V_{\text{shale}}$ curves.

**Step 1**: The shale index is derived using Equation 6.1, where $0 < I_{\text{sh}} < 1$. GR represents the GR log reading, $GR_{\text{cl}}$ the average log reading in clean sands (sand line) and, $GR_{\text{sh}}$ the average log reading in shales or shale line (Dewan, 1983). The sand and shale lines are estimated in each well for each stratigraphic interval using histogram plots; the latter shows the frequency of occurrence of a GR log reading against itself (Figure 6.3a).

$$I_{\text{sh}} = \frac{GR_{\text{cl}} - GR_{\text{sh}}}{GR_{\text{sh}} - GR_{\text{cl}}}$$  \hspace{1cm} (Eq. 6.1)

**Step 2**: The shale index is transposed to $V_{\text{shale}}$ by way of linear or nonlinear conversion methods (Baker Atlas, 1995); depending on the age of the rocks. For example, pre-Tertiary consolidated rocks (Larionov equation—older rocks) and Tertiary unconsolidated rocks (Larionov equation—Tertiary, Steibner equation—Miocene to Pliocene) plot along different trend lines. It is understood that if the shale index curve remains uncorrected, $V_{\text{shale}}$ is over-estimated (Rider, 2006). The stratigraphic interval of interest (the Halibut Subgroup) spans the Campanian to Early Eocene (Figure 2.2) so that the Larionov equation—older-rocks was used to transpose $I_{\text{sh}}$ to $V_{\text{shale}}$ (Equation 6.2); this same correction was used in the Otway Basin (Lyon et al., 2005a; Lyon et al., 2005b), located immediately west of the Gippsland Basin.

$$V_{\text{shale}} = 0.33(2^{I_{\text{sh}}}) - 1$$  \hspace{1cm} (Eq. 6.2)

**Step 3**: Clean sandstones and pure shales are typically associated with a low and high GR log curve response, respectively, although the response is not unique to those lithologies. For example, coal
and carbonate will also often be associated with a low GR response (Figure 6.3c–d). Heavy minerals, arkosic and mica/glaucocitic sandstones are associated with a high GR response, similar to that of shale, while shaly coals and igneous rocks can be expected to have variable GR responses (Rider, 2006). The implication of the presence of similar GR responses from different rock types is that using the $V_{\text{shale}}$ curve alone could result in assigning a wrong lithology. For example, a potential breach of trap across-fault would normally be recognised by identifying zones of juxtaposed low-to-low $V_{\text{shale}}$, followed by estimating the SGR within those zones; it follows that the fluid transmissivity could also be misinterpreted. To account for any potential misidentification, coal, carbonate and volcanics/volcaniclastics were identified from wireline logs, and estimates of thickness made for each of the 11 wells used in the fault seal analysis.

**Step 4**: The $V_{\text{shale}}$ curve, generated from the natural GR log, was compared against:

- core, where possible (Grunter-1, Kipper-1 and -2, Tuna-1; Appendix 3: Table A3.1);
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- the thorium (Th) log, where available (Scallop-1 and Grunter-1), and;
- the $V_{\text{shale}}$ curve generated from the Th log (Scallop-1, Grunter-1).

The thorium log enables sandstones (Av. Th = 1.7 ppm, Figure 6.3b), particularly arkoses, to be differentiated from shales (Av. Th = 12 ppm), something that the natural GR log cannot give. Further, the thorium log is also used to more comprehensively differentiate shale; Rider (2006, p77) states ‘thorium is a very good shale indicator’.

The Th log-generated shale index curve was derived using Equation 6.3, where $0 < I_{\text{sh}} < 1$, Th represents the Thorium log reading and, $Th_{cl}$ and $Th_{sh}$ the average log reading in clean sands and shales, respectively (Rider, 2006). The $V_{\text{shale}}$ curve, generated from the Th log, is then computed from the $I_{\text{sh}}$ curve using Equation 6.2.

\[ I_{\text{sh}} = \frac{Th - Th_{cl}}{Th_{sh} - Th_{cl}} \quad (\text{Eq. 6.3}) \]

### 6.3.3 Juxtaposition analysis and modelling shale smear

*TrapTester*™ provides two approaches for projecting log-derived attributes and/or assigned lithology from the wellbore onto the fault plane: *well curve mapping* and *isochore mapping* (Badley Geoscience Ltd, 2008). For sparse well control, it is more appropriate to use *well curve mapping* as opposed to *isochore mapping*\(^{31}\). The latter methodology is applied where individual reservoirs can be differentiated. In the Gippsland Basin, although the producing reservoirs are known, this information has not been published. The principle underlying *well curve mapping* is to project the $V_{\text{shale}}$ curve by proportionally scaling the stratigraphic interval from an adjacent wellbore, onto the corresponding interval on the fault plane. Any potential breach of sealing across a fault plane is indicated by zones of juxtaposed low-to-low $V_{\text{shale}}$ and/or SGR. Ultimately, the *well curve mapping* approach relies on the appropriateness of the sand and shale-line estimations, as well as determining an appropriate $V_{\text{shale}}$, or SGR cut-off, to represent the fluid transmissivity across-fault. The *isochore mapping* approach relies more on understanding the hydraulic properties of the sands, such as in field development, where more wells provide better constraints on the extent of facies and, the pressure communication between sands is known. In this study, only the *well curve mapping* method was used to project the $V_{\text{shale}}$ curve across the fault plane and estimate the $V_{\text{shale}}$ attribute.

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\(^{31}\) Eleven wells are present within the study subarea (c. 200 km\(^2\)), equating to 18 km\(^2\) per well, considered sparse for the study area (Figure 6.1).
Direct evidence of fault gouge\textsuperscript{32} (e.g. shale smear, cataclasis, brecciation, mylonisation of disaggregation zones), normally obtained from core, is nonexistent. In the absence of fault rock samples, an alternative is to use smear factors, such as the clay smear potential (CSP)\textsuperscript{33}, shale smear factor (SSF)\textsuperscript{34} or SGR. The fundamental difference between the CSP/SSF and the SGR is that the former uses a morphological model to represent the structure of the clay/shale, while the latter uses a compositional model that incorporates the bulk properties of the fault rock.

In this study, the SGR was used to ascertain the potential of sealing by shale smear. The SGR is defined as the summation of $V_{\text{shale}}$ to thickness for individual beds divided by the throw (Equation 6.4) and, expressed as a percentage (Yielding et al., 1997; Freeman et al., 1998),

$$SGR = \frac{\left[\sum (V_{\text{shale}} \Delta z)\right]}{\text{throw}} \times 100\%$$  \hspace{1cm} (Eq. 6.4)

where $\Delta z$ is the thickness of individual beds. A synthesis from multiple basins suggests that a SGR of greater than 0.20 indicates a continuous shale smear, while an SGR in the range 0.15–0.20 indicates a discontinuous smear (Yielding et al., 2002). The assumptions inherent in the use of the SGR (Yielding et al., 1997; Freeman et al., 1998) are as follows:

- the proportion of sandstone and shale in the wall rock is the same as in the fault rock; this is considered a reasonable assumption, as independently demonstrated through outcrop studies (Foxford et al., 1998; Yielding, 2002);
- the sand and shale lines are taken as representing a $V_{\text{shale}}$ of zero and 100\%, respectively;
- lithologies other than sandstone and shale are not considered;
- the thickness and extent of the fault gouge is assumed to attenuate gradually towards the midway point between the footwall and hanging-wall offsets, and;
- the fault gouge is taken as being smeared equally in both the footwall and hanging-wall and, only across a single fault plane.

The module Triangle plot\textsuperscript{TM} was used for sensitivity analysis.

\textsuperscript{32} A fault gouge is defined as ‘The brittle failure of rock in shear produces multiple fractured material known as cataclastic rock or breccia. At shallow depths in the Earth’s crust, this material is non-cohesive, and is termed fault gouge.’ (Sammis et al., 1987, p777).

\textsuperscript{33} The CSP is defined as the square of the shale source bed thickness divided by the distance between the end of the downthrown and upthrown smears (Fulljames et al., 1997; Yielding, et al., 1997).

\textsuperscript{34} The SSF is defined as the throw divided by the thickness of the shale source-bed; it becomes discontinuous for SSFs greater than 5–10 although variations will occur as a result of local conditions.
6.3.4 Estimating retention capacity/CO₂ column heights

The module TrapAnalyst™ forms part of TrapTester™ software and is used to provide first-pass estimates of the retention capacity of smear-based seals (SGR-generated). The retention capacity is represented as the minimum hydrocarbon column height (\(H_{\text{hyd}}\)) that a fault trap can hold—the theoretical basis and methodology are outlined in Bretan et al. (2003). In brief, a breach of seal across-fault occurs when the buoyancy pressure pertaining to a hydrocarbon column exceeds that of a smear-based seal’s capillary entry pressure (AFEP). Workflow steps and theory are briefly outlined below.

**Step 1:** The capillary entry pressure is calculated according to equation 6.5, where the SGR is

\[
AFEP = 10^{SGR - C}
\]

Equ. 6.5

computed at each grid node on the fault plane; \(C\) is a constant relating to the depth of burial (Bretan et al., 2003). Ideally, SGR-based AFEPs could be calibrated against mercury injection capillary pressure (MICP) -based capillary entry pressures, subject to rock samples being available, and potentially, also ground-truthed against petroleum field-based reservoir pressures recorded across-fault (Yielding et al., 1997). However, calibration and ground-truthing were not carried out in this study as data were unavailable.

**Step 2:** The hydrocarbon column height (\(H_{\text{hyd}}\)) is then empirically derived using equation 6.6,

\[
H_{\text{hyd}} = \frac{dP}{g(\rho_w - \rho_h)}
\]

Equ. 6.6

where \(dP\) is the AFEP and, \(\rho_w\) and \(\rho_h\) the pore-water and hydrocarbon density at reservoir depth, respectively (Childs et al., 2002). As combined CO₂ and brine saturated reservoirs are being considered in this study, \(H_{\text{hyd}}\) and \(\rho_h\) are substituted by the column height and CO₂ density (\(H_{\text{CO₂}}\), \(\rho_{\text{CO₂}}\)), respectively (Equation 6.7). As \(\rho_w\) and \(\rho_{\text{CO₂}}\) vary with depth, these are estimated at the reservoir depth for the fault trap—CSIRO’s calculator (J. Ennis-King—Pers. Comm., Jan. 2011) is used for this purpose in combination with the structure maps generated in this study. The salinity input was 5,000 ppm (R. Daniels—Pers. Comm., Jan. 2011), while pore pressures and average temperature gradients were set to 10 MPa/km and 35°/km, respectively (see Appendix 3 for source).
Step 3: Following the above inputs and computations, TrapAnalystTM outputs a minimum, average and maximum $H_{\text{CO}_2}$ and, the associated CO$_2$–H$_2$O contact depths. The minimum $H_{\text{CO}_2}$ is then compared against the trap’s structural closure to ascertain whether the CO$_2$–H$_2$O contact depth is above it, and thus, indicating whether the trap is partly fault-seal dependant or filled-to-spill. However, the estimates are considered first-pass as the entire interval between intervening horizons was modelled as one interconnected reservoir. Individual reservoirs and intervening shale streaks were not considered as such testing was considered outside the scope of this study (see Chapter 1), and also speculative in sandstone-dominated intervals that are constrained by sparse well control.

6.4 Results

6.4.1 CO$_2$ storage leads

Faults located in the study area were described in Chapter 3, faults pertaining to CO$_2$SL-1, -2 and -3 (study subarea) are further described plotting strikes and dips on a combined stereographic projection–rose diagram (Figure 6.4a). Fault planes, intersecting seismic horizons SeahSS to LatrSS, mostly strike at 106° ± 32°N (excluding outliers), and dip to the SSW at ~ 65°–75°. However, the strike for any one fault-trace (that is sampled at a regular interval) can vary by up ± 33° (Figure 6.4b). The variation reflects the sinuosity of many of the faults located in the study subarea, many elongated (Figure 6.4c). The frequency-of-occurrence plot for fault throw (bin interval of 5 m) shows throws ranging up to 100+ m (Figure 6.4d).

CO$_2$SLs are described below with reference to the faults and traps located within. Assessing the fault seal at the updip extent of the fault trap becomes pertinent in order to assess its capacity to retain a CO$_2$ column.

CO$_2$SL-1

CO$_2$SL-1 is bounded to the north by major faults F18 and F122 and to the south by major faults F6, F14 and F20 (Figure 6.5). Both sets of bounding faults are offset by relay ramps. All fault tips arrest at the Mackerel Unconformity (MackMS horizon).

Any CO$_2$ migrating within CO$_2$SL-1 would eventually pool in one of five places (Figure 6.5), including:

- the updip limit of subleads 1a and 1b, adjacent to fault F122;
- the updip limit of sublead 1c, adjacent to the relay ramp that offsets faults F18 and F122;
- the updip limit of subleads 1d and 1e, adjacent to fault F13;
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- the updip limit of sublead 1f, adjacent to fault F18, and;
- the updip limit of subleads 1g and 1h, adjacent to faults F13 and F18 and where Stonefish-1 was drilled.

Figure 6.4. Fault strike, dip and throw summary—study subarea.
(a) Combined stereographic projection–rose diagram for all faults (strikes, poles-to-plane), (b) combined stereographic projection–rose diagram for fault F18 (strikes, poles-to-plane), (c) maximum throw, for all faults, plotted against fault-trace length, and (d) Frequency of occurrence plot (throw) for all faults.

**CO₂ SL-2**

CO₂ SL-2 is bounded to the north by the Rosedale Fault (F55), to the east by splay fault F56, to the south by faults F18 and F122 and, to the west by faults F91 and F165 (Figure 6.5). Faults F18 and
F122 are interpreted as being offset by relay ramps while faults F91 and F165 subparallel each other. Most faults arrest at the Mackerel Unconformity (MackMS horizon) with the exception of F55, F91 and F165 that arrest in a local setting within the Swordfish Formation; the underlying Cobia Subgroup sediments could act as a potential thief zone to migrating CO₂, potentially compromising trap integrity.

Any CO₂ migrating within CO₂SL-2 would eventually pool in one of six places (Figure 6.5), including:

- the structural crest of the Tuna Field (subleads 2a and 2b), although conditional upon sealing across-fault at the branch line of faults F165 and F189;
- the updip limit of sublead 2c, adjacent to the Rosedale Fault (F55);
- the updip limit of sublead 2d, adjacent to the branch line of faults F55 and F56;
- the updip limit of sublead 2e, adjacent to fault F106, and;
- the updip limit of sublead 2f, adjacent to the branch line of faults F56 and F173.

![Figure 6.5. Representative fluid-flow paths for CO₂SL-1 to -3—depth structure, faults and areas of trap breach.](image-url)
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Backdrop: depth structure of the ILHalS horizon. $S_{\text{Hmax}}$—maximum shear stress azimuth, here 139°N (van Ruth et al., 2006), yellow lines are conjugate directions/planes for shear failure determined in this study.

CO$_2$SL-3

CO$_2$SL-3 is bounded to the north by the Rosedale Fault, to the east by splay fault F19 and to the south by splay fault F56 (Figure 6.5). These three normal faults, consistently dip basinwards to the S–SSW. Splay faults F19 and F56 have been interpreted as having hard-linked branch lines, although there is some uncertainty, at depth, regarding the linkage for splay fault F19. A compressional jog has been interpreted at the intersection of faults F55 and F56; the jog also incorporates a minor fault, F214. Most faults arrest at the Mackerel Unconformity (MackMS horizon), but the upper tip-line bound for faults F19, F56, F144 and F211 extends locally to the Latrobe Unconformity (LatrSS horizon).

Three subleads exist within CO$_2$SL-3 (3a–3c, Figure 6.5). Any CO$_2$ migrating within CO$_2$SL-3 would ultimately pool at the crest of the Kipper Field structure, pooling against major bounding faults F19, F55 and minor faults F141 and F144. Other minor faults (F134, F135 and F215) within these subleads would probably only act as baffles or barriers to fluid flow, retaining only minimal CO$_2$ columns. Besides having reduced throw relative to the bounding faults, the minor faults dip to the NE and SW.

6.4.2 Stratigraphic interpretation

Average lithology percentages were calculated for each of the stratigraphic intervals considered (Table 6.1); these are briefly described below first, together with selected log evaluations. The correlations and stratigraphic intervals are then described and illustrated (Figure 6.6).

(i) The presence and/or absence of arkoses was verified where possible (Grunter-1 and Scallop-1) by comparing the spectral potassium log against the natural GR log. The result was that both sets of curves (spectral-K and natural-GR) mostly mirrored one another, with only rare occurrences of arkose. No mineral sands or soil horizons were interpreted.

(ii) The presence and thickness of volcanics/volcaniclastics were estimated from the sonic log, where the velocity was greater than 4,500 m/s. Also, volcanics/volcaniclastics could be ground-truthed against cuttings (Figure 6.6). The presence and thickness of carbonate beds was estimated from the density log where the density was greater than 2.71–2.75 gm/c$^3$, depending on the reservoir interval to which the cut off was applied (see Appendix 3: Table A3.2). Similarly, the presence and thickness of coal was estimated from the sonic log, where the
acoustic slowness was greater than 95–105 µs/ft. Refer to the caption in Table 6.1 for a description when calculating sandstone and shale thicknesses.

(iii) The lithology and respective thickness percentages, estimated from well logs, are sandstone and siltstone (71.7–89.7%), shale (1.1–16.9%), coal (3.3–10%), carbonate (0–1%) and volcanics (0–5.3%) (Table 6.1).

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Table 6.1. Thickness (m, %) of key lithologies—GBeaSS to SworSS intervals.
The thicknesses of coal, carbonate and volcanics were computed using the PetroViewPlus™ module (cut offs in Appendix 3: Table A3.2). The thickness of shale was computed using TrapTeste™s Triangle Plot module; a V<sub>shale</sub> of
0.45 was used as a cut off to differentiate sandstone–siltstone from shale. Sandstone thicknesses were obtained by subtracting the thickness of coal, shale, carbonate and volcanics from the interval’s thickness. ND—not drilled.

**GBeaSS interval**

The sandstone content is high throughout the GBeaSS interval\(^\text{35}\), ranging in thickness from 10–869.2 m (Table 6.1), but is particularly high in wells on the Strzelecki Terrace (e.g. 91% of the section in Admiral-1). The GBeaSS interval also contains volcanics/volcaniclastics (Figures 6.7–6.8) that are known to locally affect reservoir quality, for example at the Kipper Field (Sloan et al., 1992) and at Scallop-1 where the maximum volcanic/volcaniclastic thickness is 89 m. The maximum total shale thickness is 60.1 m, with five wells having thin intervals (i.e. < 2 m) and, three wells having no shale present. Individual shale beds may provide intraformational seals in the other six wells. The maximum coal thickness is 56 m; carbonate beds are absent. On the basis of lithology thicknesses alone, there is potential for shale and/or coal to form fault gouge if a source bed is entrained in the fault plane\(^\text{36}\).

Any intra-reservoir fluid transmissivity within the GBeaSS interval has independently been demonstrated by the presence of hydrocarbon zones. For example, an oil zone exists at Grunter-1. In this well, the total net sand is estimated at 23.3 m, and porosities are in the range of 12–17% (Figure 6.7). Seven gas zones are also present at Kipper-1; gas was tested at 24.9 mscf/d and condensate was also recovered. Porosities in Kipper-1 are in the range of 16–22% at 2,000 m, but reduce to 10–14% at 2,300 m. Hydrocarbons are also present in Kipper-2, Tuna-1 and Tuna-3. Both the high sandstone percentages and petroleum present in the GBeaSS interval suggest that this interval is likely to be a conduit for fluids where juxtaposed across-fault.

**LHalSS1 interval**

The sandstone to siltstone content is high throughout the LHalSS1 interval ranging in thickness from 28–444.6 m (Table 6.1), and it can comprise the entire interval, particularly in wells on the Strzelecki Terrace where the Halibut Subgroup also thins (e.g. Judith-1). The thickness of shale, coal and carbonate beds encountered ranges from 0–111.4, 0–32 and 0–8 m, respectively (Table 6.1). The shale thickness in seven of the 11 wells is less than 4 m; however, shale thickness increases downdip at Batfish-1, Grunter-1 and Stonefish-1. On the basis of lithology thicknesses alone, there is potential for shale and/or coal to form fault gouge if entrained.

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\(^{35}\) The reservoirs in the Golden Beach Subgroup (GBeaSS interval) are known as the ‘S’ reservoirs (Djakic, 1996).

\(^{36}\) ‘Entrain’ refers to the process of a rock, initially forming part of a bed (source bed) in the footwall or hanging-wall of a fault and, that gets transported into the fault as a result of fault-slip.
The high sandstone percentage within the LHalSS1 interval suggests that the interval is more likely to act as a conduit for fluids when juxtaposed across-fault with other sandstone-prone intervals. Hydrocarbons are present in Tuna-1 and Tuna-3 (Figure 6.7); thereby, suggesting indirectly that intraformational seals exist. Porosities are in the range of 13–28% (e.g. Tuna-3).

**LHalSS2 interval**

The sandstone content in the LHalSS2 interval is up to 100% in wells on the Strzelecki Terrace where the Halibut Subgroup thins (e.g. Admiral-1, Table 6.1). The thickness of shale, coal and carbonate beds encountered ranges from 0–188.6, 0–51 and 0–10 m, respectively. Shale is absent in Admiral-1, Judith-1 and Tuna-1, but present downdip at Batfish-1, Grunter-1 and Stonefish-1 (Table 6.1). The Kate Shale thickens from 7 m at Tuna-1 to 72 m at Grunter-1—the shale’s GR response is intermediate to high (90–110 API). On the basis of lithology thickness, there is potential for shale and/or coal to form fault gouge if entrained.

The high percentage of sandstone in the LHalSS2 interval suggests that it is likely to be a conduit for fluids when juxtaposed across-fault with other sandstone-prone intervals. Exceptions may exist downdip, where the Kate Shale is thicker and significant fault gouge more likely. Hydrocarbons are present in Grunter-1, Tuna-1 and Tuna-3 (Figure 6.7). The porosity range is 12–24% at Grunter-1 and Kipper-1 and -2.

**UHalSS1 interval**

The sandstone content in the UHalSS1 interval (107.7–506.5 m thick) is as high as 88% on the Strzelecki Terrace where the Halibut Subgroup thins (e.g. Admiral-1, Table 6.1). The thickness of shale, coal and carbonate beds encountered is 0–54.7 m, 13–46 m and 0–3 m, respectively. Shale is absent in Admiral-1 and Judith-1, but present downdip at Batfish-1, Grunter-1 and Stonefish-1. On the basis of lithology thicknesses alone, there is potential for shale and/or coal to form fault gouge if entrained.

The high percentage of sandstone in the UHalSS1 interval suggests that it is likely to be a conduit for fluids when juxtaposed across-fault with other sandstone-prone intervals. However, the UHalSS1 interval contains more shale and coal than other intervals, for example, 11% in Stonefish-1 and 24% in Scallop-1. Consequently, the UHalSS1 interval may have some sealing potential when juxtaposed across-fault with other sandstone-prone intervals. Hydrocarbons are present at Grunter-1, while hydrocarbon indications have been recorded elsewhere (Figure 6.7). Porosities are generally high, in the range of 13–30% at Admiral-1, Grunter-1, Kipper-1 and -2 and Stonefish-1.
Figure 6.6. Stratigraphic cross-section showing interpreted unconformities across the Latrobe Group - study subarea.
Figure 6.7. Stratigraphic cross-section showing GR logs, lithology (cuttings), shows and porosity - study subarea.
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UHalSS2 interval

The sandstone content in the UHalSS2 interval (3–112.3 m thick, Table 6.1) is high and, increases in wells located on the Strzelecki Terrace where the Halibut Subgroup thins (e.g. 75% at Admiral-1). The thickness of shale, coal and carbonate beds ranges from 0–34.7, 1–41 and 0–2 m, respectively. Shale is absent in Admiral-1, Judith-1 and Stonefish-1. All of these lithologies could form fault gouge. However, the high percentage of sandstone in the UHalSS2 interval suggests that the interval is more likely to act as a conduit for fluids when juxtaposed across-fault with other sandstone-prone intervals. Hydrocarbons are present at Tuna-3 and Kipper-1 (Figure 6.7). Porosities are in the range of 17–23%, 15–26% and 16–27% in Grunter-1 and Kipper-1 and -2, respectively.

UHalSS3, CobiSS and SworSS intervals

The sandstone content in the UHalSS3 interval is variable, being absent in places but up to 267.7 m where wells are located in the Tuna-Flounder Channel (e.g. Bt-1 in Table 6.1). The thickness of shale, coal and carbonate beds encountered ranges from 0–170.4, 0–2 and 0–1 m, respectively. All of these lithologies could form fault gouge if entrained. Hydrocarbons are present at Tuna-1 where sands of the Tuna-Flounder Channel were intersected (Figure 6.7).

The CobiSS interval comprises mainly shale with limited sandstone downdip of the Strzelecki Shelf, whilst both coal and carbonate beds are absent. The CobiSS interval will act as a local seal and, is only occasionally faulted. The overlying carbonate-bearing SworSS interval acts as a regional seal, although potentially absent in a local setting.

6.4.3 V_{shale} curves

Sand and shale lines

Sand and shale lines were estimated for each of the 11 wells and 7 stratigraphic intervals present; a typical histogram of the GR log response for one stratigraphic interval is shown in Figure 6.8, others can be found in Appendix 3 (Figures A3.1–3.2). Accordingly, the GR log values (excluding outliers) representative of the sand and shale lines (G_{cl}–G_{sh}) for the GBaaS, LHalSS1, LHalSS2, UHalSS1, UHalSS2, UHalSS3–CobiSS and SworSS intervals are 15–130, 20–145, 20–145, 15–135, 15–135, 15–115 and 15–100 API, respectively (also see Appendix 3: Figure A3.2 for other input parameters).

The V_{shale} curve generally tracks the GR log curve and is always less than 0.8 and mostly less than 0.6 (Figure 6.9), indicative of the generally sandy nature of the intervals as corroborated from cuttings (Figure 6.7). The sensitivity analysis in relation to the choice of the sand and shale lines and shale index to V_{shale} curve conversion method used follows (Section 6.4.5).
GR log/V shale curve to core comparison

The GR log and GR log-generated V shale curves for Grunter-1, Kipper-1 and -2 and Tuna-1 were compared to cores recovered from these wells—cable stretch was accounted for (Appendix 3: Figures A3.3–3.4). The sandstone and siltstone lithologies interpreted from the low GR and V shale-curve signatures are also characteristic of the cored reservoir sections. The siltstone section from the Grunter-1 core gives a reasonable match to the high GR log-curve response, although a poor match is obtained in the sandstone sections. Overall, the GR log-curve responses in Kipper-1 and Grunter-1 are higher (up to 110 API) than would be expected for sandstone and siltstone lithologies. The response is still high (up to 80 API), but more representative in Kipper-2. Additionally, the high to low GR log-curve responses observed across the 1,822 to 1,835 m transition in Kipper-1 is not reflected in the lithologies cored.

A longer section of core was recovered in Tuna-1, spanning the LongSS to UHalSS3 intervals (Appendix 3: Figure A3.4). This core has mudstone sections up to 6 m thick; such sections are useful for cross-checking the validity of the estimated shale line. However, the resulting GR log-curve response to core comparison was, overall, a poor match, with the GR log-curve values being lower than expected (i.e. < 80 API). As well, the Kate Shale was found not to have the expected highest
Figure 6.9. Stratigraphic cross-section showing GR logs and natural GR-generated $V_{\text{sh}}$ curves - study subarea.
GR response. The $V_{\text{shale}}$ curve to core comparison mirrored the GR log-curve responses with values ranging up to 0.45 for all four wells (Grunter-1, Kipper-1 and -2, Tuna-1), again lower than expected for the shale intervals specifically. The mismatch observed from the higher than expected GR and $V_{\text{shale}}$ values in sandstone-dominant intervals may suggest that the radioactive response of sandstones (i.e. having different mineral composition) needs to be accounted for, as well as, undefined location-specific factors. Taking into account such detail lies beyond the scope of this study. One ramification from this mismatch that is pertinent to this study is that a zone of high-to-high $V_{\text{shale}}$ modelled across-fault may not directly correlate to a sealing section across-fault, specifically if it is sandstone-prone.

**Upper limit of effective porosity**

Industry-based estimates of the upper limit of effective porosity are reviewed here as these can provide a benchmark to differentiate between stratigraphic intervals that are likely to reflect reservoirs, from those that will reflect seals. In Admiral-1, Kipper-2 and Judith-1, the operators estimated the cut off for effective porosity to be between 50 and 65% of the sand-to-shale line separation (ESSO., 1990, 1987b; Shell, 1990b, respectively). A 50% sand-line cut off is equivalent to a $V_{\text{shale}}$ of 0.5, if assuming a linear conversion of shale index to $V_{\text{shale}}$, and 0.33 if a nonlinear conversion is used. However, caution is required when making use of the upper limit of effective porosity estimates. In the case of Admiral-1 and Kipper-2, the sand and shale lines are based on density–neutron crossplots. These sand and shale lines are unique to each of these wells. In comparison, the sand and shale lines used in this study are unique to each of the seven stratigraphic intervals, and each average sand and shale line was derived from the 11 wells (Appendix 3: Table A3.2).

In this study, an average $V_{\text{shale}}$ of 0.45 was used to indicate the transition between reservoir (transmissivity) and seal (nontransmissivity), partly based on the fact that sandstone/siltstone lithologies recorded in core are associated with a $V_{\text{shale}}$ of less than 0.45. Independent of this study, industry-based estimates of the upper limit of effective porosity, 0.5 and 0.65, are inappropriate for gauging transmissivity here as the sand-to-shale line separation used by industry is narrower (~30–100 API) than that used across this study’s 11-well dataset (~15–145 API). The difference translates into an underestimate of the shale index by up to 25% for the 11-well dataset of this study.

**Natural GR versus Thorium GR log comparison**

Both the natural GR and Thorium GR logs from Grunter-1 and Scallop-1 were used to compare their respective $V_{\text{shale}}$ curve responses: both sets of logs were run through the PetroViewPlus™ program.
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with identical input parameters. The ASCII output of both curves was compared by calculating differences between them at the depth sample rate of 0.125 m. The maximum, minimum, average, median, mode and standard deviation were obtained for each stratigraphic interval (Figure 6.10). Excluding outliers, the average, median and mode were found to be near-coincident (~ -0.05–0.1), averaging approximately zero and the standard deviation small (i.e. ~ < 0.1). The maximum and minimum values naturally fluctuate more, being ± 0.2. These results suggest that the natural GR-generated $V_{\text{shale}}$ curve is fairly representative of shalyness, the difference observed between the natural-GR and thorium-GR-generated $V_{\text{shale}}$ curves is minimal, excluding outliers.

Figure 6.10. Comparison between natural and Thorium GR-generated $V_{\text{shale}}$ curves—error analysis.

6.4.4 $V_{\text{shale}}$ and SGR attribute mapping

The $V_{\text{shale}}$ and SGR attributes can be analysed at each horizon–fault intersection polygon, or across the fault plane as a whole. The latter method is more suited and adopted for this study as the $V_{\text{shale}}$ values are uniformly low (80% are less than 0.6, Figure 6.9). In addition, the mapped seismic horizons are not necessarily tracking at the base of a seal interval.

The transmissivity cut-off scheme pertinent to usage of the $V_{\text{shale}}$ and SGR attributes (Figure 6.11) is compatible to the scheme used by Badley Geoscience Ltd (2008). Also shown in the figure is the transition between effective fluid transmissivity and nontransmissivity based on an SGR of 0.2. This transitional value was established from outcrop studies from numerous basins (Yielding, 2002), further confirmed by comparing the SGR against retention hydrocarbon column heights in North Sea fields (Bretan et al., 2003; Bretan and Yielding, 2005). In addition, the $V_{\text{shale}}$ cut off of 0.45 (see Section 6.4.3) is qualitatively and tentatively tied to an SGR of 0.2 for transmissivity-estimation purposes.
The Traptester™ attributes Curve: \( V_{\text{shale}} \) and Curve: shale gouge ratio, were used to represent juxtaposition and sealing by shale smear, respectively. The attributes allow the level of continuity-of-seal on the fault planes to be determined. The mapped attribute patterns of the Curve: \( V_{\text{shale}} \) attribute showed mosaic to thin-layered patterns, indicating that traps that have sand-on-shale windows suitably juxtaposed across-fault would probably be localised and problematic to prove up, subject to full 3-D geomodelling being undertaken. Approximately 85–90% of the \( V_{\text{shale}} \), displayed on both the footwall and hanging-wall, is less than 0.35 (Figure 6.12a) suggesting a high likelihood of fluid transmissivity across-fault. Between 5 to 10% of the \( V_{\text{shale}} \) is between 0.35 and 0.45 suggesting some suitably juxtaposed although localised sand-on-silt/shaly silt windows may exist. Updip of Scallop-1, up to 5% of the fault plane has a \( V_{\text{shale}} \) between 0.45 and 0.75; but these latter occurrences are rare. The evidence from the \( V_{\text{shale}} \) as mapped across the fault plane suggests that faults are unlikely to hold back significant columns of reservoir fluids, especially gas. Below the SeahSS horizon, the low \( V_{\text{shale}} \) values (Figure 6.9) reflect volcanic/volcaniclastic layers, not shales (Figure 6.7). However, these volcanic/volcaniclastic layers (expected to act as seals) could be suitably juxtaposed against sandstone reservoirs, potentially providing a trap as is the case in the Kipper Field (O’Halloran and Johnstone, 2001).

Figure 6.11. Comparison of transmissivity cut-offs for the volume of shale (\( V_{\text{shale}} \)) and shale gouge ratio (SGR).

For the SGR attribute, 15% of the fault-plane has an SGR < 0.15, 60% is between 0.15 < SGR ≤ 0.25 and 25% > 0.25; a representative fault-plane example is given in Figure 6.13a. In this representative example of the SGR attribute, mapping across the fault-plane shows continuity of the attribute, although variable, with values generally less than 0.2. Thickness of intervals where SGR >
0.2 can be as high as 100–300 m in the LHalSS1 and LHalSS2 intervals, which is far in excess of the range of throws of either fault in this representative example (20–50 m), although throws can be 100 m for the deeper SeahSS horizon (Figure 6.4d).

Taking into account all faults across the study subarea, one suitable stratigraphic level for CO\(_2\) injection appears to be directly above the LHalSS horizon where a thick sand interval exists (Figure 6.13a). The SGR overlying the sand interval is continuous, several hundred meters thick and could provide a seal. In the UHalSS1 and UHalSS2 intervals, an SGR of less than 0.2 was found for bands up to 50–200 m thick, but discontinuous so that smear-based seals are more localised there. Based on the modelling evidence herein, a CO\(_2\) column could be supported via a smear-based seal, assuming entrainment of source beds.

### 6.4.5 Sensitivity analysis

A sensitivity analysis was undertaken to ascertain the relative effect of alternate parameter inputs for generating the \(V_{\text{shale}}\) curve (see Section 6.3.2), as well as in using TrapTester\textsuperscript{TM}'s curve mapper tool-generated options (this section).

**Generating \(V_{\text{shale}}\) curves**

Firstly, a sensitivity analysis was carried out to ascertain the effect of using the nonlinear shale index \((I_{\text{sh}})\) to \(V_{\text{shale}}\) conversion (i.e. second Larionov conversion method), as opposed to using a linear method. The \(V_{\text{shale}}\) curves generated for Grunter-1 and Scallop-1 were used for this sensitivity analysis. Magnitudes (ASCII format) pertaining to the \(V_{\text{shale}}\) curve were input into EXCEL\textsuperscript{TM} and, differences arising from the conversion methods used \((V_{\text{shale \ (linear)}} ~ V_{\text{shale \ (nonlinear)}})\) in the \(V_{\text{shale}}\) magnitudes were computed and, basic statistical information generated (the maximum and minimum values, average, median, mode and standard deviation—Figure 6.14). It was found that the average, median and mode ranges from 0.15 to -0.23, with the standard deviation being < 0.1 (Figure 6.14a). Overall, these statistics confirm the analytical prediction using Equation 6.2 and, consequently, substantiate that the nonlinear shale index to \(V_{\text{shale}}\) conversion was computed correctly.

Secondly, the sand line was decreased arbitrarily by 10% and, shale line increased by 10% of the sand-to-shale line separation (Figure 6.14b). The change was taken to reflect the case where a cleaner sand and shalier shale are present. The resulting average, mean and mode mirrored each other, ranging from 0.2 to -0.3 with the standard deviation being < 0.17. The maximum and minimum values are large, reflecting outliers from a heavily sampled log curve (0.15 m). These statistics indicate that the choice of the sand and shale line does change the \(V_{\text{shale}}\) attribute to the degree that
Figure 6.12. Comparison of volume of shale (V_{shale}) profiles—sensitivity analysis.
(a) Base case: input parameters—11 wells, averaging algorithm, fault tips ≠ zero throw. (b) Sensitivity to well numbers: input parameters—10 wells, East Pilchard-1 removed, averaging algorithm, fault tips ≠ zero throw. (c) Sensitivity to the algorithm used: input parameters—11 wells, hanging-wall algorithm, fault tips ≠ zero throw.
Figure 6.13. Comparison of shale gouge ratio (SGR) profiles—sensitivity analysis.
(a) Base case: input parameters—11 wells, averaging algorithm, fault tips ≠ zero throw. (b) Sensitivity to well numbers: input parameters—10 wells, East Pilchard-1 removed, averaging algorithm, fault tips ≠ zero throw. (c) Sensitivity to algorithm used: input parameters—11 wells, hanging-wall algorithm, fault tips ≠ zero throw.
care is required when making deductions regarding any sand-on-shale windows interpreted across-fault.

Thirdly, additional checks were made for log responses from specific lithologies. For example, a low GR log response, as is often found in coal (Rider, 2006), could generate the same $V_{\text{shale}}$ response as that of sandstone (compare Figures 6.3b and c). However, the coals were found to contain some clay, which is reflected in the GR magnitude, implying that any correction to the $V_{\text{shale}}$ curve would be of limited value. The volcanic lithologies are also often associated with a low GR-log response (Figure 6.7), so that the associated low $V_{\text{shale}}$ response could be mistaken for that of sandstone.
Fortunately, the volcanic layers are consistently found just below the SeahSS horizon and, can be accounted for readily when viewing \( V_{\text{shale}} \) patterns across the fault plane.

**Well curve mapping method**

Specific parameters input when using the *well curve mapper* method (used to generate the \( V_{\text{shale}} \) curve) were tested adjacent to the branch line of faults F55 and F56 (near East Pilchard-1) to ascertain sensitivities. The base case used: (1) all 11 wells to generate the \( V_{\text{shale}} \) attribute; (2) the averaging algorithm; and, (3) treated the fault tips as having non-zero throw (Figure 6.12a). The averaging algorithm calculates the \( V_{\text{shale}} \) attribute across the fault plane by incorporating the \( V_{\text{shale}} \) curves from both the footwall and hanging-wall sides. Also, the fault tips are not treated as having zero throw because section is removed at an unconformity (i.e. the seismic horizons are not stratigraphic horizons).

**Well distribution:** It is obvious that the number of wells included when generating the \( V_{\text{shale}} \) and SGR attributes will affect the attribute pattern mapped across the fault plane. To assess how pronounced the effect might be, East Pilchard-1 was excluded from the 11-well base case, and the \( V_{\text{shale}} \) and SGR attributes regenerated. The \( V_{\text{shale}} \) attribute patterns are significantly altered (Figure 6.12b) as the bias is now weighted towards the Scallop-1 well, located further to the east-southeast. Similarly, the SGR-attribute pattern also changes (Figure 6.13b). The implication is that the well distribution imposes significant control with inherent limitations on the accuracy of the attribute patterns mapped across the fault planes. Ultimately, the level of detail put into modelling attributes across the fault plane must be proportional to this inherent limitation.

**Averaging versus non-averaging algorithm:** The option exists, when using the *curve mapper* tool, to either generate the SGR attribute by averaging the \( V_{\text{shale}} \) attribute (i.e. using both the footwall and hanging-wall) or, to only take into account the \( V_{\text{shale}} \) curves extrapolated from wells located on the hanging-wall side of the fault. An SGR estimation based solely on using the hanging-wall side would not incorporate any missing section present on the footwall, where erosion may have occurred. It must be remembered that all seismic horizons interpreted within the reservoir interval of interest are unconformities. Therefore, the averaging option is considered appropriate, particularly in the area of the RFZS and RFZ. No matter which option is chosen, the sensitivity analysis shows a negligible difference in the overall mapped attribute pattern for the SGR (Figure 6.13c); \( V_{\text{shale}} \) also appears unaffected by the footwall/hanging-wall averaging (Figure 6.12c).

**Zero versus non-zero throw:** Another input option in the program allows the fault tips to be treated as having zero throw. The base case treats the fault tips as having non-zero throw, as faults arrest at
the Mackerel Unconformity (MackMS horizon), and it is the missing eroded section that makes the zero throw. Nevertheless, the ‘fault tip as zero throw’ option was tested to ascertain if any significant difference would occur. The results showed a negligible difference to the mapped attribute pattern for the SGR.

Lastly, it is postulated that minor faults may potentially have an impact on the generation of the $V_{\text{shale}}$ and SGR attributes because of the averaging inherent during the tessellation process. To test this, minor faults were deactivated and the attributes regenerated. Minor faults were found to not affect the generated $V_{\text{shale}}$ and SGR attributes.

### 6.4.6 Retention capacity—CO₂ column heights

First-pass estimates of CO₂ column heights that potentially could be retained in fault traps via shale smear are, as expected, highly variable (Table 6.2). In the case where estimates were made at the ILHalS horizon, the minimum CO₂ column heights vary from approximately 11 to 22.3 m. Accordingly, the percentage of the trap filled varies from 5–100% (based on column height alone).

<table>
<thead>
<tr>
<th>Sublead</th>
<th>CO₂/brine density (Kg/m³)</th>
<th>Minimum SGR</th>
<th>Min. CO₂ column height (m)</th>
<th>Spill points (m)</th>
<th>Leak point (m)</th>
<th>% trap fill (maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a, 1b</td>
<td>654/998</td>
<td>0.07</td>
<td>17.9</td>
<td>2350</td>
<td>2249.1</td>
<td>2231.2</td>
</tr>
<tr>
<td>1c, 1f</td>
<td>647/991</td>
<td>0.09</td>
<td>12.1</td>
<td>2700</td>
<td>2700</td>
<td>2630</td>
</tr>
<tr>
<td>1d, 1e</td>
<td>644/988</td>
<td>0.1</td>
<td>12.6</td>
<td>2840</td>
<td>2730.6</td>
<td>2718</td>
</tr>
<tr>
<td>1g, 1h</td>
<td>647/991</td>
<td>0.07</td>
<td>19.7</td>
<td>2825</td>
<td>2649.7</td>
<td>2630</td>
</tr>
<tr>
<td>2a, 2b</td>
<td>659/1002</td>
<td>0.06</td>
<td>14.1</td>
<td>2140</td>
<td>1989.6</td>
<td>1975.5</td>
</tr>
<tr>
<td>2c</td>
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<td>0.049</td>
<td>13.4</td>
<td>1960</td>
<td>1960</td>
<td>1950</td>
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<td>19.3</td>
<td>2370</td>
<td>2349.3</td>
<td>2330.3</td>
</tr>
<tr>
<td>3a</td>
<td>665/1005</td>
<td>0.02</td>
<td>11</td>
<td>2010</td>
<td>2010</td>
<td>2000</td>
</tr>
<tr>
<td>3b</td>
<td>665/1005</td>
<td>0.02</td>
<td>11.5</td>
<td>1950</td>
<td>1857.1</td>
<td>1845.6</td>
</tr>
</tbody>
</table>

| Table 6.2. Estimation of CO₂ column height and percentage of fault-trap fill at the ILHalS horizon—CO₂SL-1 to -3. CO₂ and brine densities are calculated at the reservoir-horizon depth for the fault trap—CSIRO’s calculator is used (J. Ennis-King—Pers. Comm., Jan. 2011). The minimum SGR, CO₂ column height, spill and leak points are estimated using TrapAnalysSTM. See Figure 6.5 for the location of subleads. |

The results indicate that the spill point of some traps could be potentially controlled by shale smear and not structural closure. However, the minimum CO₂ column height output by TrapAnalysSTM is based on the minimum SGR output, the latter being below the SGR normally taken as being representative of transmissivity versus non-transmissivity to fluids (see Figure 6.11), the latter an inherent limitation of the module TrapTesterSTM. It follows that the actual trap-fill percentage reduces when the SGR cut-off is raised to 0.2. Ultimately, numerous trap-fill estimates are possible for traps identified in the study area; it is only possible here to show a representative example (Figure 6.15). There, the shale smear-based versus structural-based spill point is highly dependant on the well.
control that guides the extrapolation of the SGR attribute and, the ensuing CO₂ column-height estimations. On this one model-run example, the trap is estimated to only be capable of being filled to ~ 10.1% of the structural closure and, subject to a shale smear-based seal being present.

![Figure 6.15. 3-D representation of a fault trap (fault F18) at the ILHalS horizon—CO₂SL-1g and h. The CO₂ column-height attribute is shown across the fault plane; leak, structural and shale seal-based spill points are determined using Trap Analyst™. Only fault F18 is shown, all other faults have been deactivated. Col.—column.](image)

### 6.5 Discussion

#### 6.5.1 Fault traps and sealing across-fault

The discovery of the Kipper Field, in 1986, confirmed the capability of the Kipper Shale to act as a sealing unit across-fault (Sloan et al., 1992). In the Kipper Field, minor oil accumulations present in the sand reservoirs (T-1, T-2 and T-3) are intraformationally sealed within the lower Halibut Subgroup, within a fault-independent, low-side rollover, although part of the column may have a sealing component across-fault. The principal 342 m oil and gas column in the Kipper S-1 sand reservoir (Golden Beach Subgroup) is trapped in a fault-dependent closure. The trap comprises the 470 m thick Kipper Shale that acts as a lateral fault-plane seal and, is top-bounded by a volcanic-based seal. The structure is probably filled to spill. The contribution of known volcanic flows, volcanioclastics and cones to the sealing across-fault is uncertain. Volcanics are present across the study subarea (Figure 6.6) and these may act as a top seal for intra-Golden Beach Subgroup reservoirs, as is the case in the Kipper Field (O’Halloran and Johnstone, 2001).

The sealing capacity of the intraformational shales of the Halibut Subgroup was confirmed by the 200 MMbbl oil accumulation in the heavily faulted rollover present at the Flounder Field (ESSO
Chapter 6—Juxtaposition analysis and modelling shale smear

Australia Ltd, 1988; Younes, 1988); this field is located south of the study subarea. However, at Grunter-1 and Stonefish-1, intraformational seals have failed to trap hydrocarbons in the T-1 and T-8 reservoirs (Young, 2007). Elsewhere, at the Tuna Field, a detailed stratigraphic study concluded that the trapping of the oil and gas columns is structurally-controlled rather than stratigraphically-controlled (Wagstaff et al., 2006). However, in the Halibut Field, hydrocarbon trapping is mainly stratigraphically controlled, although a structural component has recently been demonstrated (Gross et al., 2008). Ultimately, understanding the aquifer support during production is fundamental in differentiating the contribution of structural versus stratigraphic control as demonstrated from production in the Tuna Field (Santamaria and Fish, 2003). The above confirms that both hydrocarbon-bearing intraformationally sealed structural and stratigraphic traps exist, in addition to fault traps previously discussed.

The confining pressure under which structures form can affect both the presence and type of fault seal. For example, low confining pressure conditions are thought to be conducive for brittle faulting to occur along single fault planes, whilst high confining pressure conditions are thought to favour the formation of fault clusters, of either brittle or ductile deformation (Fisher and Knipe, 1998). Associated fault smears are often continuous for faults that are offset by extensional-based dip relays (low confining pressure), because it is common for the source bed to be entrained into the fault zone during extension. The presence of extensional-based dip relays (or dilatational jogs) is also conducive to the formation of diagenetic cements (Fisher and Knipe, 1998); some Australian examples have been documented in the Vulcan Sub-basin (O’Brien and Woods, 1995). In comparison, smears in contractional dip relays (high confining pressure) are more likely to be discontinuous (Faerseth, 2006). Also, high strain is expected in wide fault zones where microfaulting is present, while low strain is expected in narrow fault zones (Fisher and Knipe, 1998). In the case of the study subarea, the dominance of multibranched minor en echelon dilatational jogs that subparallel the Rosedale Fault, should favour the presence of continuous fault gouge when considering the above criteria alone. In comparison, any fault gouge associated with compressional jogs, as may be present adjacent to the Tuna and West Tuna Field structures and adjacent to the branch line of faults F55 and F56, is predicted to be discontinuous.

In the absence of direct fault-rock measurements, demonstrating a link between fault displacement and smear continuity is pertinent to the discussion involving fault-trap integrity. For example, large throws were found to be associated with shale smear factors (SSF) that were much lower than those estimated for small throws (Table 6.3; Sperrevik et al., 2000; Faerseth, 2006). Therefore, although small-scale faults could have more effective smear-based seals, these cannot be used to predict the
continuity of smear-based seals associated with large-scale faults. Estimating the effectiveness of sealing by shale smear using point counting methods is also constrained by the similar limitation of scale. However, the continuity of clay-smear, for North Sea hydrocarbon field examples, has been shown to both vary and, to not necessarily conform to SSF predictions (Fisher and Knipe, 1998). It was also noted that in some cases the continuity of smear was more closely related to the grain size of the phyllosilicates, with discontinuous smears being associated with fine-grained clays. Elsewhere, the sealing capacity of most shales has been attributed to the planar fabric of the clay (Eichhubl et al., 2005). Because of the preceding discussion, the modest fault displacements found in the study subarea (< 200 m) should favour a high continuity for any smear-based seal.

Table 6.3. Smear continuity contrasted against fault throw.

### 6.5.2 Modelling shale smear

In the study subarea, any fault rock, either present in fault zones or along fault planes, mostly originates from a mixed sediment source, comprising 71.7–89.7% sandstone/siltstone, 1.1–16.9% shale and 6–13.1% for coal, carbonate and volcanics (Table 6.1). This compositional range is equivalent to Faerseth’s (2006) category-2 fault rock, which is associated with discontinuous smear and having an intermediate fault seal risk. In comparison, a shale-sourced fault rock may be more likely in the depocentre located to the south of the study subarea. A shale layer-sourced smear would be equivalent to Faerseth’s (2006) category-1 fault rock that is associated with a continuous smear and has a low fault seal risk.

The presence, nature and sealing capacity of fault rocks is first subject to the entrainment of the associated source beds. In the absence of direct fault-rock data being available, the SGR provides an estimate of sealing potential; an SGR of ~ 0.2 is taken as the approximate transition point between continuous and noncontinuous smear-based seals (Yielding, 2002). The hydrocarbon-bearing fault trap of the Kipper Field confirms that fault-traps, either via sand-on-shale windows across-fault or via shale smear, are viable in the study subarea (Sloan et al., 1992). Nevertheless, the presence, nature, and sealing potential of fault rocks are also dependent on a multitude of factors that make regional fault-seal prediction problematic. For example, depth of burial links to sedimentary alteration processes (e.g. diagenesis, disaggregation, pressure solution, cataclasis and cementation), which ultimately shape the fault rock; the fault rock’s capillary entry threshold pressure
changes accordingly (Fisher and Knipe, 1998). Now, pertinent factors affecting and/or, linked to, smear-based seals are discussed below; these include fault-rock composition, source-bed composition and entrainment and, retention capacity of top seals.

**Fault rock and source-bed composition and, entrainment**

The study of fault rocks is relevant to fault-trap integrity in that capillary entry pressures will vary according to composition and related deformation processes within the fault zone. For example, clay-matrix gouge zones have lower permeability, higher capillary entry pressures and smaller pore throat sizes than found in associated cataclastic deformation bands: cf. \( K = 0.024 \text{ mD and } \Phi = 13.1\% \) versus \( K = 8.0 \text{ mD and } \Phi = 28.8\% \), respectively (Gibson, 1998). Both the deformation process and quality of the fault rock within a fault zone vary depending on the phyllosilicate content (Fisher and Knipe, 1998), as follows.

(i) Fault rocks that contain continuous coherent domains have a minimum phyllosilicate content of 40%.

(ii) A fault rock, sourced from a clay-rich siliciclastic rock, will tend to seal by disaggregation and grain boundary sliding, the reason being that clay (i.e. phyllosilicates) can deform by grain sliding, grain rotation and plastic deformation without the need for grain crushing or dilation processes. By way of example, a phyllosilicate content around 15% can result in deformation by particulate flow and, filling of the intergranular porosity.

(iii) A fault rock sourced from an impure sandstone will tend to seal by cataclasis and post faulting pressure solution.

(iv) A fault rock sourced from a clean sandstone will tend to seal by cataclasis and post deformation quartz cementation.

Fault rocks in the study area can be expected to be mainly sourced from phyllosilicates in areas that are distal to the basin margin (i.e. towards the southeast), from siliciclastics in areas proximal to the basin margin and, from clay-rich siliciclastics in intermediate basin settings. It follows that the fault-rock composition and associated deformation process will probably vary along the length of the Rosedale Fault zone, and within the study subarea. However, based on the lithology-percentage estimates, a mixed clay-rich siliciclastic to impure sandstone source-bed is postulated.

The impact of changing source-bed composition (i.e. shale to coal), thickness, or stratigraphic position on the estimation of the SGR can be demonstrated analytically. Test cases 1 to 3 (Figure 6.16a–c) are representative, in part, of the Golden Beach and Halibut Subgroup stratigraphy in the
study subarea—case-1 is taken as the base case. Coal has been established as a potential source of fault smear based on outcrop studies (Faerseth, 2006). As such, coal has been arbitrarily assigned a value of 0.7, equivalent to the average $V_{\text{shale}}$ of the shale beds. The outcomes of the analytical derivations are set out in what follows.

(i) Case-1: The average GR varies from 0.28 to 0.41 (Figure 6.16d) for throws that vary from 20 to 100 m when the source beds being entrained comprise 50% sandstone and 50% shale (Figure 6.16a).

(ii) Case-2: The average SGR varies from 0.48 to 0.55 (Figure 6.16d) for throws that vary from 20 to 100 m when the source beds being entrained comprise sandstone, coal and shale (Figure 6.16b). In case-2, 25% of the sandstone beds have been replaced by coal beds, with the replacement $V_{\text{shale}}$ being 0.7. An 88% change in the SGR occurs when comparing case-2 to case-1 (Figure 6.16e).

(iii) Case-3: The SGR varies from 0.30 to 0.52 (Figure 6.16d) for throws that vary from 20 to 100 m when the source beds being entrained comprise sandstone, coal and shale (Figure 6.16c). In case-3, 10% of the sandstone beds have been replaced by coal beds, with the replacement $V_{\text{shale}}$ being 0.7. A change of up to 33% in the SGR occurs when comparing case-3 to case-1 (Figure 6.16e).

These generic cases illustrate the sealing potential of coal, if/when entrained into a fault zone, thereby implying that it may be important to account for nonclastic lithologies, assuming these can be modelled. Of further importance is the relative depth of the source bed. For example, an immature sandstone sourcing a smear at the deep end of the fault plane will have a higher SGR, than a clean sandstone sourcing a smear at shallower depths (Gibson, 1998). The SGR’s depth and lithology dependency should be accounted for in more detailed studies, but are beyond the scope of this study. Coal-bearing seals are not as effective as an equivalent shale-bearing seals because in coal, CO$_2$ is fully wetting at all reservoir pressures, which reduces the comparative effectiveness of its sealing potential (Daniel and Kaldi, 2008). However, coal-bearing seals can still act as permeability baffles or barriers, assuming both adequate seal continuity and thickness of the fault gouge. With regard to the latter, the entry threshold pressure for a coal-bearing fault rock was found to be directly proportional to the thickness of the fault zone (Sperrevik et al., 2002).

Selective entrainment of a source bed can occur (Faerseth, 2006; Faerseth et al., 2007); in the Black Diamond Mines of California, shale was entrained in the fault zone whereas sandstone was not (Eichhubl et al., 2005). This is probably a function of the shear strength of individual source beds.
Figure 6.16. Calculating the shale gouge ratio (SGR)—understanding the contribution of coal.
Generic cases 1 to 3 are representative, in part, of the gross lithology present in the Golden Beach and Halibut Subgroups (excluding volcanics/volcaniclastics and carbonates).
For example, the relative shear strength of sandstone and shale beds was in some cases found to be more important than the shear strength and mineral composition of the clay itself (Sperrevik et al., 2000). In low shear-strength sandstones, the shale clays react in a brittle way and produce no smear, whereas in high shear-strength sandstones the shale clay has a ductile response. Unfortunately, the absence of shear-strength data in this study prevents any corroboration of this.

Retention capacities—top seal and sealing across-fault

The potential effectiveness of sealing by shale smear can be gauged by considering top seals in relation to the inferred hydrocarbon/CO\textsubscript{2} column heights that these can potentially hold. For the study area, MICP-derived entry threshold pressures\textsuperscript{37} and estimated CO\textsubscript{2} retention heights are available for the regional seal (SworSS interval), the local seals of the Cobia Subgroup and intraformational seals of the upper Halibut Formation (Table 6.4). Only shales have been analysed; there are no MICP analyses of siliciclastic-based fault seals in the study subarea, so that predicting the sealing potential of the latter is problematic.

<table>
<thead>
<tr>
<th>Well</th>
<th>Depth MD (m)</th>
<th>Stratigraphic intervals</th>
<th>Seal type</th>
<th>Threshold pressure (psia)</th>
<th>CO\textsubscript{2} column height (m)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobia-A11</td>
<td>2617.7</td>
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<td>91</td>
<td>1</td>
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<td>317</td>
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<td>Intraformational</td>
<td>2924</td>
<td>317</td>
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<td>99</td>
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<td>Local seal</td>
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<td>671</td>
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</table>

Table 6.4. Top seal capacity of regional, local and intraformational seals—study area.

The seal capacity estimated from CO\textsubscript{2} column heights, assuming a fully wetting phase for the CO\textsubscript{2} and a contact angle of zero, are in the range of 41–962 m (Table 6.4). These estimated column heights reduce by 50% for a non-fully wetting phase for the CO\textsubscript{2} and, where the contact angles range up to 60° (Daniel and Kaldi, 2008). In either case, the potential seal capacity is considerable in either case. Empirical evidence for the general sealing capacity of regional top seals is also

\textsuperscript{37} The threshold pressure is the pressure at which the non-wetting phase (mercury or CO\textsubscript{2}) begins to flow through the rock as a continuous phase (Daniel and Kaldi, 2004).
demonstrated by the presence of major petroleum fields. The sealing capacity is considered excellent for the seals of the Halibut Subgroup, but is considered less for intraformational seals, although demonstrated to be favourable in the Flounder Field (ESSO Australia Ltd, 1988; Younes, 1988).

The variation and low fault-trap fill percentages estimated using TrapAnalyst™ were anticipated for the sandstone-dominated stratigraphic intervals present in the study subarea. Further, the minimum column-height retention capacities associated with smear-based seals is considerably less than the top-seal retention capacities discussed above. It is impractical in this study to fully capture, detail and demonstrate the column-height retention-capacity potential for both sand-on-shale windows (juxtaposed) across-fault and, shale-smear-based seals. However, the sensitivities assessed, particularly the sparse well spacing, do illustrate the uncertainty and limitations when modelling fault-seal retention capacities.

6.6 Conclusions

The juxtaposition analysis and modelling of shale smear has demonstrated the following.

(i) The juxtaposition analysis, based on the $V_{\text{shale}}$ attribute, indicates that sand-on-shale windows across-fault could exist within the LHalSS1 and LHalSS2 intervals, although probably only local in extent. However, within the UHalSS1 and UHalSS2 intervals, $V_{\text{shale}}$ is mostly less than 0.35 and sand-on-sand windows across-fault are unlikely to be sealed. It is inferred that the volcanics topping the GBeaSS interval at the Kipper Field oil accumulation could also provide suitable sand-on-volcaniclastic windows across-fault, although this remains untested.

(ii) Modelling shale smear, based on the SGR attribute, indicates that sand-on-sand windows across-fault could be potentially sealed across sections of the fault plane, but not across its entirety. Also, the shale-smear extent along-slip was found to mostly exceed the average slip across most fault planes.

(iii) Using either a combined footwall–hanging-wall algorithm or, a hanging-wall only algorithm, does not alter SGR attribute estimates, as was also found when invoking a zero versus non-zero throw at the fault tip. However, the across fault-plane mapping of the $V_{\text{shale}}$ and SGR attributes were demonstrated to be most sensitive to the number and/or distribution of wells used when generating these attributes.

(iv) Lithologies, other than sandstone/siltstone and shale, are present within the GBeaSS to CobiSS intervals; coal averages up to 10% of the interval, carbonate up to 1% and
volcanics/volcaniclastics up to 5.3%. These could source some error when generating the SGR attribute because the derivation equation for the SGR does not account for these lithologies. Errors of up to 90% were shown to be possible under specific coal percentage–thickness combinations—a more detailed study would be required to account for this source of error.

(v) Minimum CO₂ column heights, potentially retained by shale-smear and across portions of the fault plane, are small (< 23 m) in comparison to top-seal retention capacities (< 962 m). A 3-D model of individual reservoirs and seals across the study subarea would be required to demonstrate the study subarea’s full potential in respect to CO₂ column-height retainment across-fault. Key sensitivities (e.g. number and/or distribution of wells), as established in this study, would need to be addressed.

(vi) The estimation of fluid transmissivity across-fault would require ground-truthing of juxtaposition or shale-smear-based seal cases against known hydrocarbon columns. This may be possible to achieve in the hydrocarbon-bearing reservoirs present in the GBaSS interval (e.g. Kipper Field, CO₂SL-3), although any resulting ground-truthing would be site-specific. Uncertainty would still remain with respect to remaining CO₂SLs.
7.1 Introduction

The juxtaposition analysis, described in Chapter 6, indicates that sand-on-shale windows across-fault are possible, but are unlikely to be maintained across fault planes that extend up to 20 km along-strike. However, the shale-smear modelling indicates that localised sealing is possible, subject to shale gouge/smear being present and continuous across the fault plane. In this chapter, fault reactivation modelling is used to further test fault integrity for conditions where reservoirs are subjected to increased pore pressure (e.g. simulating CO₂ injection).

In situ principal stresses are important inputs into fault reactivation modelling. In situ principal stresses were first interpreted in the Gippsland Basin for the purpose of predicting the susceptibility of natural fractures to fluid flow (Nelson, 2002). Further interpretations were carried out to constrain the in situ state of stress in the eastern Gippsland Basin (Nelson et al., 2005; Nelson and Hillis, 2005; Nelson et al., 2006a), as well as in southeastern Australia (Nelson et al., 2006b). Also, in situ principal stresses, determined from these studies, were input into geomodels to ascertain trap integrity: all for cases where reservoirs are being subjected to increased pore pressure (e.g. simulating CO₂ injection). Examples include the Kingfish Field reservoir studies (van Ruth and Nelson, 2005; van Ruth et al., 2006) and Northern Gas Route studies (Root et al., 2004; Gibson-Poole et al., 2006a; Gibson-Poole et al., 2008b).

To-date, fault reactivation modelling has mostly relied on geomodels derived from 2-D fault interpretations (Root et al., 2004; van Ruth et al., 2006), with only one case study based on 3-D seismic data (van Ruth and Nelson, 2005; Gibson-Poole et al., 2006a; Gibson-Poole et al., 2008b). As far as the author can determine, no fault reactivation modelling has ever been carried out on complex fault arrays, where minor faults, branch lines and the upper tip-line bound are included in combination with juxtaposition analysis and shale smear modelling.

In Chapter 7, the failure-mode conditions under which such faults reactivate are determined, with an emphasis on synthesizing the effect of minor ‘splay’ faults and branch lines within the array. The workflow has two components, first to model the slip tendency, dilation tendency, slip stability and fracture stability of all faults including minor splay faults and, second to carry out a sensitivity analysis on the geomechanical–structural parameters critical to estimating the likelihood of reactivation.
7.2 Geomechanical concepts

Geomechanical analysis defines and ascertains the contemporary *in situ* stress field and, fault reactivation modelling makes use of the *in situ* stress field to estimate the likely failure of individual faults according to the failure envelope assigned to the rock matrix and/or fault rocks. Relevant parameters required for input to fault reactivation modelling include estimating the *in situ* principal stress tensor, fault orientation and dip, coefficient of static friction (µ), cohesion (C) and, prevailing reservoir fluid pore pressure (P_P) (Streit and Hillis, 2002). The level of increased pore pressure (ΔP) that is sustainable by each fault in the faulted reservoir system is termed in this study the likelihood of fault reactivation. The most critically stressed faults have the highest likelihood of reactivation and are more likely to conduct fluids (Sibson, 1996; Barton et al., 1997). This likelihood of reactivation is also a measure of the overall integrity of any trap associated with the fault. Ideally, a calibration of ΔP against known hydrocarbon columns in intact traps, as well as a comparison of ΔP magnitudes in breached traps, is required to refine trap-breach prediction.

7.2.1 The stress tensor

Stress (σ) is defined as the average force acting over an area, a concept introduced in continuum mechanics, and used here to associate it to the state of stress. The state of stress in a body can be represented in a Cartesian coordinate system by a nine-component Cauchy stress-tensor (matrix 7.1),

$$\sigma = \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$  \hspace{1cm} \text{(Matrix 7.1)}$$

where $\sigma_{11}$, $\sigma_{22}$ and $\sigma_{33}$ are vectors depicting stresses normal to the faces of an infinitesimally small cube and where $\sigma_{ij}$, for $i \neq j$, are vectors depicting shear stresses parallel to the faces of this cube. In practice, it is possible to find three orthogonal planes in a homogenous stress field, for which $\sigma_{ij} = 0$ and where $i \neq j$. The 9-component matrix then reduces to a 3-component matrix (Matrix 7.2); with the components normally abbreviated to $\sigma_1$, $\sigma_2$ and $\sigma_3$ (Jaeger and Cook, 1976).

7.2.2 Principal stress

In geology, the term *in situ* stress is frequently used to refer to present-day crustal stresses. In Australia, the regional crustal stresses have been interpreted from *in situ* measurements (i.e. boreholes), mostly from within sedimentary basins (Hillis and Reynolds, 2000; 2003).
In a geological context, stresses normal to a fault plane ($\sigma_N$) are referred to as normal stresses, and stresses parallel to a fault plane ($\tau$) as shear stresses. Anderson (1951) recognised that because the earth’s surface is incapable of sustaining shear stress it must be a principal plane of stress, with the other two principal planes of stress being orthogonal to it. It follows that the state of stress, for any point within the earth, can be represented by the 3-component stress tensor $S$ (Matrix 7.2),

$$
S = \begin{bmatrix}
\sigma_1 & 0 & 0 \\
0 & \sigma_2 & 0 \\
0 & 0 & \sigma_3
\end{bmatrix}
$$

(Matrix 7.2)

where $\sigma_1, \sigma_2, \sigma_3$ are the maximum, intermediate and minimum tensor components. It was further recognised (Jaeger and Cook, 1976) that the state-of-stress tensor could be fully represented by the maximum horizontal stress ($S_{H\text{max}}$), minimum horizontal stress ($S_{H\text{min}}$) and vertical stress ($S_V$), coupled with the azimuth of $S_{H\text{max}}$; noted in this study as $S_{H\text{max}\theta}$. Also, note that the parameters $S_{H\text{max}}, S_{H\text{min}}$ and $S_V$ are represented either as magnitudes (MPa) or gradients (MPa/km).

Anderson (1951) also recognised that knowledge of the relative magnitudes of $S_{H\text{max}}, S_{H\text{min}}$ and $S_V$ allowed both the fault regime and conjugate directions of shear failure to be estimated (Figure 7.1). For example, a normal fault regime is implied when $S_V > S_{H\text{max}} > S_{H\text{min}}$, a reverse regime when $S_{H\text{max}} > S_{H\text{min}} > S_V$ and a strike-slip regime when $S_{H\text{max}} > S_V > S_{H\text{min}}$.

**NOTE:**
This figure is included on page 217 of the print copy of the thesis held in the University of Adelaide Library.

*Figure 7.1. Conjugate planes of shear failure in differing fault regimes—classification after Anderson (1951).*
7.2.3 Effective stress

Fluid within a porous rock imparts a pore pressure, such that the stress required to deform this saturated rock is lower than for an equivalent nonporous rock (Equation 7.1). The effective principal stress is defined as:

\[ S' = S - P_p \]  
\[ \text{Eq. 7.1} \]

where \( S' \) is the effective stress tensor (denoted by the inflection '), \( S \) is the 3-component stress tensor (Matrix 7.2), and \( P_p \) is a constant. Thus, an increase in pore pressure of 10 MPa/km yields an effective stress magnitude that is 10 MPa/km lower than the absolute stress magnitude (Figure 7.2), so moving Mohr’s circles closer to the failure envelope (described in the next section).

![Figure 7.2. Effect of pore pressure at a reservoir depth of 2.5 km—study subarea. Parameters used in this study: \( P_p, S_{\text{Hmax}}, S_{\text{V}} \) and \( S_{\text{ Tmin}} \)=10, 42, 21 and 20 MPa/km, respectively. Two failure envelopes are shown (see Section 7.3.1).](image)

7.2.4 Mohr’s circle

Mohr’s circle is a 2-D graphical representation of the state of stress at a point in the earth and resolves the shear and normal stress acting on all possible planes in space. Mohr's circle is adapted, according to whether a 2-D or 3-D state of stress is being considered and enables the pole to the fault plane (pole-to-plane) to be compared against the failure envelope(s), the latter based on the cohesion (C) and coefficient of static friction (\( \mu \)) (see Section 7.3.1 for description). The locus where the pole-to-plane is most proximal to the failure envelope establishes where a given fault plane is most susceptible to reactivation.

According to Mohr’s theory, both \( \sigma_N \) and \( \tau \) can be derived for any fault-plane orientation if \( \sigma_1, \sigma_2 \) and \( \sigma_3 \) are known. The above applies to a 3-D state-of-stress case. Where a fault plane is parallel to any two principal stress directions (Figure 7.3a), the pole-to-plane will plot on the circumference of one of the Mohr circles (Figure 7.3b), and is algebraically represented in Equation 7.2,
Chapter 7—Fault reactivation modelling

\[ \sigma_{xy} = \frac{1}{2} [\sigma_i + \sigma_j] + \frac{1}{2} [\sigma_i - \sigma_j] \cos 2\theta \]  
(Eq. 7.2a)

\[ \tau = \frac{1}{2} [\sigma_i - \sigma_j] \sin 2\theta \]  
(Eq. 7.2b)

where \( i \neq j \) and \( i \neq j \). If the fault plane is neither parallel nor orthogonal to any of \( \sigma_1, \sigma_2 \) or \( \sigma_3 \), then the pole-to-plane will plot within an area defined by the intersection of Mohr’s circles (Figure 7.3b), the position varying according to the dip of the fault.

\[ \sigma_1, \sigma_2, \sigma_3 \] - principal stress axes

Figure 7.3. Mohr’s circle and failure envelopes.
(a) Convention used to depict normal and shear stresses. (b) 3-D representation of Mohr’s circle showing where poles-to-plane plot. (c) Mohr’s circle and failure envelopes, also depicting where anticipated modes of failure plot. Redrafted after Jaeger et al. (2007).

7.2.5 Rock failure criterion and envelope

Several rock failure theories that incorporate rock failure envelopes exist (Jaeger et al., 2007); these include the Coulomb-Navier, Mohr and Griffith theories. The Coulomb-Navier and Mohr theories are
Chapter 7—Fault reactivation modelling

cconcerned with fracture mechanisms occurring at the macroscopic scale where fault planes can be identified. In contrast, the Griffith theory of brittle fracture considers critical stress criteria for crack propagation: it is therefore more suited to modelling failure at the microscopic scale and for representing tensile failure. Only the Coulomb-Navier and Mohr theories are relevant to this study and are described further below.

Byerlee’s analysis of rock friction

Byerlee’s (1978) analysis of rock friction is a natural starting point for describing rock failure. The relationship between \( \sigma \) and \( \tau \) was first expressed algebraically in the 17th century through Amonton’s relationship (Equation 7.3),

\[
\tau = \mu \sigma_N
\]  
(Eq. 7.3)

where \( \mu \) is the coefficient of static friction (Jaeger et al., 2007). More recently, the following empirical expressions

\[
\tau = 0.85 \sigma_N \text{ for } \sigma_N < 200 \text{ MPa} \]  
(Eq. 7.4a)

\[
\tau = 50 + 0.6 \sigma_N \text{ for } 200 < \sigma_N < 1,700 \text{ MPa} \]  
(Eq. 7.4b)

have been found, by means of rock mechanical analyses, to be representative for a broad range of common rock types (Byerlee, 1978). These expressions are known as Byerlee’s relationship for rock friction and these form part of the foundation of modern rock mechanics (Jaeger et al., 2007).

Coulomb failure criterion

The Coulomb failure criterion is an envelope that defines the limit of rock strength (Jaeger and Cook, 1976); it is algebraically represented by Equation 7.5,

\[
\tau = C + \sigma_N \tan \Phi
\]  
(Eq. 7.5)

where \( C \) is the internal resistance to sliding friction at zero normal stress (also termed cohesive strength or cohesion), and \( \Phi \) is the slope of the failure criterion envelope, which represents the angle of sliding friction (if \( C = 0 \)), or internal friction (if \( C \neq 0 \); also see Figure 7.3c). Rock strength can be estimated through empirical equations based on \( \Phi \) (Chang et al., 2006); and these can be used as an alternative to using \( C \) and \( \mu \). Also, rock strength depends on the mineralogical makeup and, whether or not, the host rock has previously been subjected to external forces and been fractured (i.e. fault rock or pre-existing weaknesses present). If the host rock is unfractured or considered intact, then frequently \( C \neq 0 \); except when considering the case of a weak rock (e.g. shale) where \( C \)
can approach zero. If the host rock is fractured, then $C$ approaches 0 and, the rock is considered to exhibit cohesionless frictional failure. However, previously fractured rocks can be healed through diagenesis and, in such cases, $C \neq 0$.

The conjugate directions for shear failure can be calculated using the second Coulomb failure criterion (Equation 7.6),

$$\tan 2\theta = -\frac{1}{\mu}$$  (Eq. 7.6)

where $\theta$ is the angle between the conjugate direction of shear failure and $S_1$ (Jaeger and Cook, 1976). A value $\mu = 0.6$ will be representative of a rock undergoing cohesionless frictional failure (Handin, 1969); in such a case $\theta = 29.6^\circ$. Values of $\mu$ vary according to rock type, although typical $\mu$ values for intact/fractured/healed rocks are in the range $0.6 < \mu < 1$ (Byerlee, 1978); also, $\theta = 45^\circ$ in the case where $\mu = 1$. The link between the variables $\theta$, $\Phi$, $C$, $\mu$, $\sigma_N$ and $\tau$ are illustrated in Figure 7.3c.

### 7.3 Methodology

#### 7.3.1 Geomechanical input

*In situ* principal stresses

The maximum *in situ* shear stress orientation ($S_{H\text{max}}$) can be estimated by interpreting borehole breakouts (BO) and drilling induced tensile fractures (DITF), $S_{h\text{min}}$ can be estimated from leak-off or hydraulic fracture tests, $S_V$ by integration of density logs, and the $S_{H\text{max}}$ magnitude can be constrained from BOs and DITFs (Hillis et al., 1993). It is beyond the scope of this study to interpret *in situ* principle stresses so published estimates have been used (summarised in Table 7.1). Also, the mean $S_{H\text{max}}$ has varied from study to study, from 130°N (Hillis et al., 1998), to 138°N following interpretation of additional BOs and DITFs (Nelson, 2002) and most recently to 139°N, when additional DITFs were incorporated (van Ruth and Nelson, 2005; van Ruth et al., 2006). A standard deviation for $S_{H\text{max}}$ of ± 12° was estimated in the Kingfish-Field study (van Ruth et al., 2006).

As shown in Table 7.1, the stress field in the study area is borderline strike-slip to reverse, trending into a reverse faulting regime with depth (Strei t, 2003; Root et al., 2004). The reservoir intervals considered in this study occur at relatively shallow depths (< 3 km), so that the stress field $S_{H\text{max}} > S_V \geq S_{h\text{min}}$ established by these authors is thought to be most representative. Accordingly, a strike-
slip fault regime is taken as the base case in this study; with $S_{\text{Hmax}} = 42$, $S_V = 21$ and $S_{\text{hmin}} = 20$ MPa/km taken as the best current estimates (Table 7.1).

<table>
<thead>
<tr>
<th>Project</th>
<th>$S_{\text{Hmax}}$</th>
<th>$S_{\text{hmin}}$</th>
<th>$S_V$</th>
<th>$P_p$</th>
<th>$S_{\text{Hmax}}(\theta)$</th>
<th>State of stress</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gippsland NA NA NA NA 130 NA</td>
<td>NA</td>
<td>(Hillis and Reynolds, 2000; Hills and Reynolds, 2003)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>West Tuna 40 20 20–22 138</td>
<td>$S_{\text{Hmax}} &gt; S_V &gt; S_{\text{hmin}}$ (1 km) $S_{\text{Hmax}} &gt; S_V &gt; S_{\text{hmin}}$ (3 km)</td>
<td>(Nelson, 2002)</td>
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</tr>
<tr>
<td>Basin 46.4 19 21.6 10 130</td>
<td>$S_{\text{Hmax}} &gt; S_V &gt; S_{\text{hmin}}$ (&lt; 1.5 km) $S_{\text{Hmax}} &gt; S_{\text{hmin}}$ ~ $S_V$ (&gt; 1.5 km)</td>
<td>(Streit, 2003)</td>
<td></td>
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</tr>
<tr>
<td>Gas route 41 18 20 10 130</td>
<td>$S_{\text{Hmax}} &gt; S_V &gt; S_{\text{min}}$ (&lt; 1.5 km) $S_{\text{Hmax}} &gt; S_{\text{hmin}}$ ~ $S_V$ (&gt; 1.5 km)</td>
<td>(Root et al., 2004; Root, 2005)</td>
<td></td>
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<tr>
<td>West Tuna 40–44 20.5 20.5 9.8 138</td>
<td>$S_{\text{hmax}} &gt; S_{\text{hmin}}$ ~ $S_V$</td>
<td>(Nelson et al., 2005)</td>
<td></td>
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<tr>
<td>West Tuna 39–42 20 20–22 9.8–10.5 139</td>
<td>$S_{\text{Hmax}} &gt; S_{\text{min}}$ ~ $S_V$</td>
<td>(Nelson and Hills, 2005)</td>
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<tr>
<td>Kingfish, West Tuna 40.5 20 21 10 139</td>
<td>$S_{\text{Hmax}} &gt; S_{\text{hmin}}$ ~ $S_V$</td>
<td></td>
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<td></td>
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<tr>
<td>West Tuna 40 20 20–22 10 138</td>
<td>$S_{\text{hmax}} &gt; S_{\text{hmin}}$ ~ $S_V$</td>
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<tr>
<td>Gippsland 40 20 20–22 10 139</td>
<td>$S_{\text{Hmax}} &gt; S_{\text{hmin}}$ ~ $S_V$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range 39–46.4 18–20.5 20–22 9.8–10.5 130–139</td>
<td>$S_{\text{Hmax}} &gt; S_V &gt; S_{\text{hmin}}$ (3 km)</td>
<td>NA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>This study 42 20 21 10 139</td>
<td>$S_{\text{Hmax}} &gt; S_V &gt; S_{\text{hmin}}$ (3 km)</td>
<td>NA</td>
<td></td>
<td></td>
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</table>

Table 7.1. Estimates of principal in situ stresses and pore pressure—Gippsland Basin.

1 This value was determined from the frictional limit envelope ($\mu = 0.6$). 2 Values determined from the power function provided. 3 Low number refers to a depth of ~ 1 km, a high number to a depth of ~ 3 km. NA—not available, $P_p$—pore pressure, $S_{\text{Hmax}}$—maximum principal stress, $S_{\text{hmin}}$—minimum principal stress, $S_V$—vertical principal stress, $S_{\text{Hmax}}(\theta)$—maximum shear strength orientation. Units for in situ principal stress—MPa/km.

Cohesive strength and coefficient of static friction

Cohesive strength and associated failure envelopes are most reliably estimated when the mechanical properties of both the reservoir and fault rocks are known (Dewhurst et al., 2002). To the author’s knowledge, no cored fault rock is available for Gippsland Basin formations. An alternative is to estimate $C$ and $\mu$ from cored reservoir intervals (Figure 7.4): in the Kingfish study, $C$ and $\mu$ were estimated at $5.4 < C < 13.5$ MPa and $0.78 < \mu < 0.9$ (van Ruth and Nelson, 2005; van Ruth et al., 2006). For some West Tuna Field core samples, multistage triaxial tests were carried out on low porosity low permeability sandstones (i.e. hard rock) belonging to the Latrobe Group and, a $C = 13.5$ MPa and $\mu = 0.9$ were determined for an applied uniaxial compressive strength of 60 MPa (Nelson et al., 2006a). For a shale (i.e. soft rock from the Lakes Entrance Formation), a $C = 8$ MPa and $\mu = 0.6$ were determined for an applied uniaxial compressive strength of 30 MPa. Estimates of $\mu$ and $C$ are also available from core samples of Baleen Field wells in the northern part the study area (Wu et al., 2000 in OMV Australia Pty Ltd., 2000). These estimates were originally made to predict potential sand production and wellbore failure during petroleum production (OMV Australia Pty Ltd., 2000) and, are used here to provide additional comparative cohesive strength and friction coefficient measurements. However, these measurements are from Burong Formation cores; a formation that is stratigraphically higher than the Mackerel Unconformity, being directly above the reservoir interval of.
interest (i.e. Halibut–Golden Beach Subgroups). Other cohesive strength measurements, such as those from Holster (1996) are more relevant to this study and have been used for comparison.

The relative absence of data on rock strength properties limits the accuracy of the fault reactivation modelling so that C has to be estimated indirectly since data is scarce. In this study, rock lithology percentages are used to infer whether the bulk rock is likely to be hard or soft, thus also inferring the associated cohesive strength on a qualitative basis. Petrophysically-derived, average lithology percentages for the Halibut–Golden Beach Subgroups are estimated at 81% sandstone, 10% shale and 9% for other lithologies (see Table 6.1). Together, these percentages are representative of a clay-rich siliciclastic rock. Additional estimates for C and µ are also available within TrapTester™'s lookup table, as follows: a cataclasite (C = 4 MPa, µ = 0.75), a disaggregation zone (C = 0 MPa, µ = 0.75) and a pure phyllosilicate fault rock (C = 0.5 MPa, µ = 0.6) (Dewhurst and Jones, 2003).

Regarding these estimates, Fisher and Knipe (1998) have demonstrated that clay-rich siliciclastic rocks will tend to seal by disaggregation and grain boundary sliding, an impure sandstone will tend to seal by cataclasism and postfaulting pressure solution, whilst a clean sandstone will tend to seal by cataclasism and postdeformation quartz cementation (discussed in Section 6.5.2).

Note 1: C and µ used by Dewhurst and Jones (2003) are based on core taken from other basins (values taken from TrapTester™'s lookup table).
Note 2: C and µ used by Holster (1996) and van Ruth et al. (2006) are laboratory-derived from core of the Kingfish Formation, Gippsland Basin.
Note 3: C and µ used by Root et al. (2004) and in this study are empirical-based estimates.
Note 4: C and µ used by Wu et al. (2000) in OMV Australia Pty Ltd (2000) are laboratory-derived from core of the Burong Formation, Gippsland Basin.

Figure 7.4. Plot of cohesion versus coefficient of static friction—study subarea.
From consideration of the above lithology percentages, measured and inferred $C$ and $\mu$ estimates and TrapTester™s lookup table, fault rocks are estimated as most likely being intermediate between a cataclasite and a disaggregation zone, so that $C = 2$ MPa and $\mu = 0.75$ are taken as being representative of the Halibut–Golden Beach Subgroup. However, faults are present in the study area so that rocks cannot be considered intact. For example, natural fractures are known to exist; as interpreted from FMI logs for West-Tuna-Field wells and at East Pilchard-1 (Nelson, 2002). Nevertheless, the values chosen for $C$ and $\mu$ are considered conservative, and not too dissimilar to values used by other researchers (Figure 7.4).

### 7.3.2 Mode-of-failure attributes

In TrapTester™, the use of a likelihood-of-fault-reactivation stereogram allows the pole-to-plane (azimuth and dip) to be superimposed on a colour-coded backdrop that depicts the magnitude of the mode-of-failure attribute (Figure 7.5). The conjugate planes of shear failure can also be plotted on the stereogram. The TrapTester™ program outputs poles-to-plane, for any one fault, based on the gridding interval used (here 100 m). Secondly, the TrapTester™ program allows mode-of-failure attributes to be visualised on a 3-D representation of the fault plane, which is particularly useful for visualising detail at branch lines and fault tips. Four mode-of-failure attributes are used: dilation tendency, slip tendency, slip stability and fracture stability. Thirdly, poles-to-plane are equally represented on a Mohr diagram (Figure 7.5). Lastly, a significant constraint when using mode-of-failure attributes is that the TrapTester™ program only allows one value of $C$ and $\mu$ and, one set of in situ principal stresses to be applied across the entire fault surface for any single model run. Furthermore, it must be emphasised that the mode-of-failure attributes only provide a ‘relative’ estimation of the likelihood of fault reactivation, not an ‘absolute’ estimation.

Dilation tendency ($T_D$) estimates the likelihood of fault failure in extension (tensile fracturing) and is defined as the normal stress acting on a fault plane normalised to the differential stress (Equation 7.7).

$$T_D = \frac{\sigma_1' - \sigma_N}{\sigma_1' - \sigma_3'}$$  
(Eq. 7.7)

Dilation tendency is independent of $\mu$ and $C$, but dependent on $S_{Hmax}$. The greater $T_D$, the likelier a fault will fail by dilation; this occurs when the pole-to-plane plots at 90° relative to $S_{Hmax}$ (Figure 7.5a). Dilation tendency was initially introduced by Ferrill et al. (1999) for the purpose of assessing the likelihood of fault reactivation in a radioactive waste repository in the Yucca Mountain, Nevada (U.S.A.) and was later adapted to faults in sedimentary basins (Mildren et al., 2002).
Figure 7.5. Mode-of-failure attributes: (a) dilation and (b) slip tendency and, (c) slip and (d) fracture stability.
Chapter 7—Fault reactivation modelling

Slip tendency ($T_s$) estimates the likelihood for a fault to reactivate via shear fracturing and is defined as the shear-to-effective normal stress acting on a fault plane (Equation 7.8).

$$T_s = \frac{\tau}{\sigma'_n}$$  

(Eq. 7.8)

The slip tendency attribute is computed under the assumption that faults are cohesionless ($C = 0$) with $\mu$ set to be 0.6. The greater $T_s$, the greater the likelihood that the fault will slip in shear; this occurs when the pole-to-plane plots at 90° relative to either of the conjugate directions of shear failure (Figure 7.5b). How one classifies $T_s$, as either high, moderate or low, is somewhat arbitrary, although $T_s$ has been classed as high if $0.6 < T_s < 1$ (Streit and Hillis, 2002). Slip tendency was initially used to estimate the relative risk of earthquakes occurring as a result of slip (Morris et al., 1996) and, later adapted to faults in sedimentary basins (Mildren and Hillis, 2002).

Slip stability ($S_s$) estimates the increase in $\Delta P$ required to cause slip on a cohesionless fault (e.g. $C = 0$) where $\mu = 0.6$. Slip stability, also known as the critical pressure perturbation (Mildren et al., 2002a), was first used to investigate, and risk, fault-seal breach for traps in North Sea basins (Wiprut and Zobach, 2002). Similarly, fracture stability estimates the $\Delta P$ required to reduce the effective stress sufficiently to cause shear, extensional shear or extensional failure on an intact/healed fault. Fracture stability is dependent on the fault azimuth, $C$, $\mu$ and the tensile strength. The lower the slip or fracture stability ($\Delta P$), the likelier the fault will reactivate. Both the minimum slip and fracture stability occur when the pole-to-plane plots at 90° relative to either of the conjugate directions of shear failure (Figures 7.5c–d). Values of $C$ and $\mu$ are critical, but often poorly constrained. Nonetheless, making use of both the slip and fracture stability attributes facilitates a comparison between end-point rock-strength cases. Lastly, unless otherwise stated the modelled $\Delta P$s, referred to in following sections, pertain to the base case (see Table 7.1).

7.4 Results

7.4.1 Fault reactivation—stand-alone faults

Dilation and slip tendency

The differential stress, defined as $\sigma_1 - \sigma_3$, is consistently high basinwide; based on current in situ principal stress interpretations (Nelson and Hillis, 2005; Nelson et al., 2006b). In the study area, $\sigma_1 - \sigma_3$ is $\sim 22$ MPa/km or $\sim 11$ times the rock tensile strength ($T$); where $T$ is $\sim 2$ MPa. Tensile failure is analytically predicted to occur when $(\sigma_1 - \sigma_3) < 4T$ (Sibson, 1996), and shear failure occurs when $(\sigma_1 - \sigma_3) > 6T$ (Sibson, 1996). Therefore, with respect to the study subarea, shear failure is predicted to occur before tensile failure, since $(\sigma_1 - \sigma_3)$ is $\sim 11T$. 

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Irrespective of the above, the dilation tendency attribute \( (T_D) \) was generated for all faults to estimate their susceptibility to tensile failure; \( T_D \) will vary as the fault plane curves so that it is given as a range for any one fault. Poles-to-planes mapping shows that the fault planes that are near-optimally aligned for tensile failure to occur, are those striking subparallel to \( S_{H_{\text{max}}} \) (at any dip), where mostly
\[ 0.4 < T_D < 1 \] (Figure 7.6a). Some exceptions exist, where lower \( T_D \) magnitudes occur for faults F91, F151, F155, F165, F173, F178 and F214; all NE–SW-trending reverse faults located in the Tuna and West Tuna Fields are included in this fault set. No trends, unique to either major or minor faults are recognised using the dilation tendency attribute, when plotting poles-to-planes on a stereogram.

The slip tendency attribute \( (T_S) \) indicates that the susceptibility of faults to slip varies considerably (Figure 7.6b). However, the mean slip tendency is generally high (0.42) relative to a maximum \( T_S \) of 0.6. There are some exceptions, being faults F141, F143, F151, F206 and F212, where a lower than average slip tendency exists. No trends unique to either major or minor faults are differentiated using the slip tendency attribute when plotting poles-to-planes on a stereogram.

**Slip and fracture stability**

The slip stability attribute indicates that for most faults a relatively low \( \Delta P \) will induce slip. Indeed, some poles-to-planes exceed the failure envelope when viewed on a Mohr diagram (Figure 7.5c). As a result, there is a high likelihood for reactivation for optimally orientated cohesionless faults (\( C = 0, \mu = 0.6 \)). By way of summary, 41% of faults only require an increase in \( \Delta P \) of < 10 MPa before the likelihood of reactivation is considered high; similarly, 77% of faults require an increase in \( \Delta P \) < 20 MPa. The previous percentages can be deduced by subtracting 9.33 MPa from the fracture-stability magnitudes in Figure 7.6c (the origin of the value 9.33 MPa is illustrated in Figure 7.5d). Exceptions exist, such as faults F91 and F165, which have high calculated \( \Delta P \) values of ~ 62 and ~ 59 MPa, respectively.

In the case of an intact/healed rock (\( C = 2 \) MPa, \( \mu = 0.75 \)), the \( \Delta P \) estimated by fracture stability is greater than in the cohesionless fault case (Figure 7.5d). As shown in Figure 7.5d, a minimum \( \Delta P \) of 9.33 MPa is required to bring an optimally orientated fault to failure (also see Figure 7.6c). Similarly to the case of the slip stability attribute, 41% of faults only require an increase in \( \Delta P \) of < 19 MPa and 77% of faults an increase in \( \Delta P < 29 \) MPa. As was the case for slip stability, the NE–SW-trending reverse faults (F91 and F165) bounding the western limb of the Tuna and West Tuna Fields are the least likely to be reactivated (Figure 7.7b), as is also the case for faults F18, F20, F55, F104, F123, F139, F151, F173 and F214. Similar NE–SW-trending faults elsewhere in the study area include those associated with the Flounder Field and Pilotfish structures located south of the study subarea (see Chapter 3). Should the cohesive strength be between the intact/healed (i.e. \( C = 2 \)) and
cohesionless (i.e. $C = 0$) end cases, then the calculated $\Delta P$ will be proportionally lower than for the intact/healed case (compare Figures 7.7a and b).

Figure 7.6. Likelihood of fault reactivation estimated from mode-of-failure attributes (dilation, slip, fracture stability).
(a) Dilation tendency ($T_D$). (b) Slip tendency ($T_S$). (c) Fracture stability ($\Delta P$, MPa). Magnitudes obtained by overlaying poles-to-plane on stereograms that portray the relevant attribute. $P_S$, $S_{Hmax}$, $S_V$, $S_{hmin} = 10, 42, 21$ and $20$ MP/km, respectively. $S_{Hmax} = 139^\circ \text{N}$. See Figures 7.7–7.8 for location of major bounding faults.
Chapter 7—Fault reactivation modelling

Modelled $\Delta P$s plotted on a Mohr diagram or stereogram can be further represented by mapping the fracture stability attribute directly on the fault planes themselves (Figure 7.7). One key observation is that high $\Delta P$s are found across portions of most fault planes, where the remaining portion of the fault-plane is at risk of reactivation (Figure 7.8a). For example, $\Delta P$ magnitudes have been modelled in excess of 20 MPa across portions of stand-alone faults F6, F13–F14, F18, F20 and F122; a consequence of fault-strike variation along any one fault plane. For example, the fault-strike variation associated with F18 is up to $\pm 33^\circ$ (see Figure 6.4b) and, the $\Delta P$ varies accordingly (compare subleads 1c and 1f—Figures 7.9a and b). In the preceding analysis the $\Delta P$ magnitude has been averaged across the seven mapped seismic horizons. However, when $\Delta P$ is not averaged, the $\Delta P$ magnitude at each horizon is nevertheless consistent; the exception being the LongSS horizon (Figure 7.9a). This exception is probably due to the greater uncertainty in defining the fault plane at depth.

7.4.2 Fault reactivation—branched faults

Demonstrating seal integrity at branch lines (by modelling) is required in the case of multibranched fault traps; specifically, for the purpose of estimating their capacity to retain columns of CO$_2$, as is done with petroleum accumulations (Gartrell et al., 2004; Gartrell et al., 2005; Langhi et al., 2010). To this end, the difference in strike for master–splay fault combinations is first estimated (Figures 7.10a–c), followed by estimating the associated difference in $\Delta P$ (Figures 7.10d–e). Finally, the difference in $\Delta P$ either side of a branch line is compared to assess the effect of splay faults on trap integrity (Figure 7.10f); results are as follows.

(i) The majority of master and splay faults trend WNW–ESE to NW–SE (see Figure 5.12). The difference in mean strike ($\Delta_{\text{strike}}$) between the master and splay faults ranges up to $-88^\circ$, the mean being $-40^\circ$ (Figure 7.10a) with $\sim 50\%$ of master–splay fault combinations having a $\Delta_{\text{strike}} < 30^\circ$.

(ii) The likelihood of a fault being reactivated is partly dependent on its strike relative to $S_{H_{\text{max}}}^9$ (139°N). Here, the difference between a fault’s strike and $S_{H_{\text{max}}}^9$ (Figures 7.10b–c) is compared to the difference between the direction of conjugate shear failure and $S_{H_{\text{max}}}^9$ (dashed lines, Figures 7.10b–c); thus, enabling the fault set to be visually represented as to its likelihood of fault reactivation. For master faults, the azimuthal difference ranges from $-84^\circ < [\Delta_{\text{strike}} - 139^\circ] < 19^\circ$ (Figure 7.10b), the mean being $-40^\circ$. Although the strike of master faults fluctuates, it is mostly $< 139^\circ$N (except for F56 and F189) and, trends WNW–ESE. In

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38 $\Delta$—this symbol is used here to mean ‘difference’; it is consistently used as such in the field of mathematics.
comparison, the azimuthal difference for splay faults ranges from $-64^\circ < \Delta \text{strike} - 139^\circ N < 62^\circ$, the mean being $-6^\circ$. The strike of splay faults fluctuates more than that of master faults, with most faults trending NW–SE (compare Figures 7.10b and c). It can be seen that a significant number of splay faults are near-parallel to $S_{\text{Hmax}}$; thus, susceptible to fault reactivation (compare magnitudes to the dotted lines).

(iii) Delta-P magnitudes have been grouped into classes to facilitate the comparison of the likelihood of fault reactivation, as follows. The likelihood of fault reactivation is considered high if $9.33 \leq \Delta P < 15 \text{ MPa}$, moderate if $15 \leq \Delta P < 20 \text{ MPa}$ and low if $\Delta P \geq 20 \text{ MPa}$ (Figure 7.8a). On this basis, 29% of master faults have a low, 58% a moderate and 13% a high likelihood of fault reactivation (Figure 7.10d). Similar to the master faults, 42% of splay faults have a low, 45% a moderate and 13% a high likelihood of fault reactivation (Figure 7.10e).

(iv) Lastly, the impact of splay faults on fault reactivation potential with a trap is examined by comparing the mean difference in $\Delta P$ estimated either side of the branch line ($\Delta[\Delta P]$) at each of the seismic horizons (LongSS–MackMS, Figure 7.10f).

Examples of $\Delta[\Delta P]$ are discussed for four key branch-line locations (Figures 7.8c–f).

- Branch line F55–F135 is key to sublead 3a having an effective trap (Figures 7.8a, c). The $\Delta P$ on the F135 side of the branch line is lower than on the F55 side, increasing the likelihood of reactivation by way of the splay fault at the branch line (Figure 7.10f).

- The major bounding or master faults F91, F151 and F165, located in the Tuna and West Tuna Fields (Figure 7.7a), have a low to moderate likelihood of fault reactivation; these faults are key to subleads 2a–2b having an effective trap. However, all but one (F178) of the associated splay faults (F35, F93, F120, F154, F155, F185, F189 and F198) act to reduce the $\Delta P$ at the branch line (Figure 7.10f). For example, the $\Delta P$ for F120 is lower than the $\Delta P$ for either F91 or F165 (Figure 7.8d), increasing the likelihood of fault reactivation by way of the splay fault at both branch lines.

- Branch line F55–F56 is key to sublead 2d having an effective trap (Figures 7.8a, e); as can be seen, the splay fault (F56) is less likely to reactivate than the master fault (F55). This is shown in Figure 7.10f by way of a positive $\Delta[\Delta P]$; however, the $\Delta[\Delta P]$ is observed to increase with depth, as a result of the fault-plane curvature adjacent to the branch line (Figure 7.8e). The latter observation demonstrates the potential sensitivity of $\Delta P$ estimates to fault-plane curvature; hence, a need for accurately interpreting the fault plane.
– Branch line F56–F173 is key to sublead 2f having an effective trap (Figures 7.8a, f); as can be seen, the splay fault (F173) is less likely to reactivate than the master fault (F56). The Scallop-1 well tested a fault closure that links to the branch line, F56–F173. The well was dry, perhaps due to leakage at this branch line; which in turn would be due, most likely, to movement on F56, rather than on F173.

– The impact of splay faults is considered negative (or detrimental to trap integrity) for 32%, positive for 26% and, the change being minimal for the remaining 42% of branch-line cases considered.

The above observations can be related to each sublead (Figure 7.8a), as follows.

**Subleads 2a–2b:** The splay faults across sublead 2a have the effect of increasing the overall likelihood of the associated branch-line reactivation; considered moderate to high (Figure 7.10f). This is, in part, due to the strike of most splay faults being subparallel to that of the conjugate planes of shear failure (Figure 7.10c); thus, resulting in low ΔPs (Figure 7.10e). However, faults F91, F151 and F165, all NE–SW trending faults, have a low likelihood of branch-line reactivation (Figure 7.10d).

**Sublead 2c:** Three of the five splay faults (F180, F151 and F181) across sublead 2c have the effect of reducing the overall likelihood of the associated branch-line reactivation (Figure 7.10f). This is, in part, due to the strike of those splay faults differing significantly with respect to that of the conjugate planes of shear failure (Figure 7.10c); thus, resulting in high ΔPs (Figure 7.10e). However, this overall reduction is mainly due to F151 where an extreme ΔP occurs (30 MPa). Therefore, the overall likelihood of branch-line reactivation is considered high.

**Sublead 2d:** Splay faults across sublead 2d have the effect of reducing the likelihood of the associated branch-line reactivation (Figure 7.10f). This is, in part, due to the strike of both splay faults differing significantly with respect to that of the conjugate planes of shear failure (Figure 7.10c); thus, resulting in slightly higher ΔPs (Figure 7.10e). An additional breach-of-trap risk in sublead 2d is the fact that the upper tip-line boundary at the F55–F56 branch line arrests above the Mackerel Unconformity (MackMS horizon; Figure 7.8a). The overall likelihood of reactivation is considered high.

**Sublead 2f:** Splay fault F173, across sublead 2f, has the effect of reducing the overall likelihood of reactivation at the branch-line contact with F56 (Figure 7.10f). Nevertheless, the overall likelihood of branch-line reactivation is still considered high, because of the low ΔP modelled on master fault F56 (Figure 7.10d).
Figure 7.7. Fault reactivation modelling ($\Delta P$)—study subarea, (a) cohesionless case and, (b) intact/healed case.

(a) Cohesionless case ($C = 0$ MPa, $\mu = 0.6$); only master bounding faults are labelled. (b) intact/healed case ($C = 2$ MPa, $\mu = 0.75$).
Figure 7.8: ΔP magnitudes at branch lines and at critical parts of stand-alone faults. (a) map and, (b - f) fault planes.

(a) Likelihood of fault reactivation - study subarea. Parts (b) to (f) show the ΔP modelled on a master fault, versus that on a splay fault, and thus, the potential effect of the latter with respect to trap integrity at the branch line. (b) Subleads 1d, 1e, 1g and 1h;
(c) Sublead 3a, (d) Sublead 2a, (e) Sublead 2d and, (f) Sublead 2f.

Legend

<table>
<thead>
<tr>
<th>Likelihood of fault reactivation</th>
<th>Stand-alone faults/other selected positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low if ΔP ≥ 20 MPa</td>
<td>Red symbol</td>
</tr>
<tr>
<td>Moderate if 15 ≤ ΔP &lt; 20 MPa</td>
<td>Yellow symbol</td>
</tr>
<tr>
<td>High if 9.33 ≤ ΔP ≤ 15 MPa</td>
<td>Blue symbol</td>
</tr>
</tbody>
</table>

Note 1: ΔP derived for intact healed faults (C = 2 MPa, μ = 0.75)
Note 2: take off 9.33 MPa for cohesionless fault (C = 0, μ = 0.5).

Sublead boundary - maximum extent of the CO₂ flow-path

Fault-Horizon intersections at different seismic horizons

H, L - structural high, low
T - 3D well location
Branch line arrests at LatSS, elsewhere at MaxxMS horizon

Note 1: only selective faults shown outside CO₂SL-1 to -3.
Note 2: depth structures (m) of ILH1S horizon used as backdrop.
CO₂SL-1 subleads 1a, 1b, 1c, 1d, 1e, 1f, 1g and 1h
CO₂SL-2 subleads 2a, 2b, 2c, 2d, 2e and 2f
CO₂SL-3 subleads 3a, 3b and 3c.
Figure 7.9. Comparison of $\Delta P$ at horizons LongSS–IUHalS for (a) stand-alone faults and, (b) fault F18. See Figure 7.8a for location of subleads.
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Figure 7.10. Fault reactivation estimations—differences in strike and ΔP for branched faults (master, splays). Δ—denotes ‘difference’, as used in mathematics. S_{max}—139°N. ΔP—Pore pressure increase. (a) Difference in mean strike between master and splay faults—negative values imply that the strike of splay faults is greater (relative to north). (b) Difference in mean strike between master faults and S_{max}—negative values imply strike of master faults < 139°N. Dotted lines—denote azimuthal difference between conjugate planes of shear failure and S_{max}, calculated for μ = 0.75; the dotted lines permit a visual comparison of whether master faults are likely to reactivate. (c) Difference in mean strike between splay faults and S_{max}—negative values imply that the strike of splay faults < 139°N. Dotted lines as per Figure 7.10b. (d) ΔP for master faults—ΔP is presented as a range as the strike of any one fault varies across the study.
Subleads 3a, b and c: To facilitate description, subleads 3a to c are merged. Splay faults across subleads 3a to c have a positive effect on the overall likelihood of the associated branch-line reactivation (Figure 7.10f). However, the overall likelihood of branch-line reactivation is still considered high as ΔPs for the master faults are still low (Figure 7.10d). Additionally, the upper tip-line bound of faults F56 and F141 arrests post the Mackerel Unconformity (MackMS horizon; Figure 7.8a), potentially increasing the trap-breach risk. Irrespective of the ΔP predictions, a successful fault trap formed, as evidenced from F19 having a proven seal across-fault and, the trap retaining a significant hydrocarbon column as part of the Kipper Gas Field structure (Sloan et al., 1992).

Overall, the likelihood of branch-line reactivation is considered moderate to high as many master and splay faults have low ΔPs associated with them. When considering all subleads, noteworthy observations are as follows.

(i) The faults least likely to reactivate are the NE–SW-trending reverse faults (F91, F151 and F165) that bound subleads 2a and 2b, encompassing the greater Tuna–West Tuna Field structure (Figure 7.8a). There, sustainable ΔP magnitudes range up to 48 MPa; a low likelihood of fault reactivation was modelled for both the cohesionless and intact/healed fault cases (compare Figures 7.7a and b). This fault stability has probably contributed to both the accumulation and preservation of the petroleum accumulated in the greater Tuna–West Tuna Field structures.

(ii) Other branch lines less likely to reactivate are F55–F214 and F56–F214 (in subleads 3a to c), F93–F185 (in sublead 2a) and F165–F155 (in sublead 2b). However, all of these branch lines incorporate splay faults that are secondary to the main fault traps, so that the ramifications are less important to the CO2 storage of the respective subleads.

7.4.3 Sensitivity analysis

$S_{Hmax}$ and $S_{Hmax^8}$

Values quoted in the literature for mean $S_{Hmax}$ range from 39–46.4 MPa/km (Table 7.1); a mean of 42 MPa/km (interpreted from borehole data) is used for the base case in the fault reactivation modelling that follows (also quoted in Nelson and Hillis, 2005; Nelson et al., 2006b). However, in other studies, an empirically-derived best fit (RMS minimisation) equation was used to define a working $S_{Hmax}$ (Table 7.2); there, the range extends to 39–48 MPa/km (Table 7.2).
Table 7.2. Estimates of principal in situ stresses at depth based on linear and power functions.

*the power functions were computed from interpreted $S_{\text{min}}$ measurements, as these were not included in the publication.

Figure 7.11. Sensitivity of the fracture stability ($\Delta P$) attribute to a +10° rotation of $S_{\text{Hmax}}$ (from 139 to 149°N).

(a) Major bounding/master faults F55, F91 and F165 projected onto a Mohr diagram. (b) Major bounding/master faults F55, F91 and F165 projected onto a stereogram. (c) Minor faults F57, F146–147, F151, F178–181 and F189 projected onto a stereogram. $P_r$, $S_{\text{Hmax}}$, $S_{\text{V}}$ and $S_{\text{min}}$—10, 42, 21 and 20 MP/km, respectively. $S_{\text{Hmax}}$—rotated to 149°N; poles to planes remain stationary. Reservoir depth—2.5 km.
A mean $S_{H_{\max} \theta}$ of 139°N was used in the base case for the fault reactivation modelling (Table 7.1). As noted previously a standard deviation of ±12° was estimated for wells in the study subarea (van Ruth et al., 2006). However, $S_{H_{\max} \theta}$ estimates for wells WT-8 and WT-37 from the West Tuna and Tuna Fields were found to be higher, 148°N (see Appendix 3—Table A3.3); possibly reflective of localised structural complexity, as has been seen elsewhere (e.g. the Otway Basin—Camac et al., 2004).

The mode-of-failure attributes were tested for sensitivity to the standard deviation by setting $S_{H_{\max} \theta}$ to 149°N, to reflect a +010°N variation, inline with estimates for the West Tuna and Tuna Fields. This change did not significantly increase or decrease the likelihood of fault reactivation for faults with respect to the failure envelope (Figure 7.11a). However, at this larger $S_{H_{\max} \theta}$, some of the major bounding faults (F55, F91 and F165) are marginally less susceptible to reactivation, as evidenced by comparing the poles-to-planes mapped on a stereogram (Figure 7.11b, visually rotate all features by +010°N except poles-to-planes). In contrast, most splay faults plot on a part of the stereogram where the $\Delta P$ is low (Figure 7.11c); for such faults, a marginal increase of +010°N has a negligible effect on the likelihood of fault reactivation.

$S_{h_{\min}}$ and $S_V$

A mean $S_{h_{\min}}$ of 20 MPa/km was used in the base case for the fault reactivation modelling (Table 7.1) where $S_{h_{\min}}$ ranges from 18–20.5 MPa/km. For $S_V$, a mean of 21 MPa/km was used although $S_V$ does range from 20–22 MPa/km, as estimated in both the onshore and offshore parts of the Gippsland Basin (Nelson et al., 2006b). However, many of the in situ principal stress estimates are derived from leak-off tests taken in the shallow Seaspray Formation (van Ruth and Nelson, 2005; van Ruth et al., 2006); and so, may not be representative of the situation at depth. Here, a sensitivity analysis with respect to $S_{h_{\min}}$ and $S_V$ is not carried out because of the narrow data spread observed. However, any minor change to $S_{h_{\min}}$ or $S_V$ could change the fault regime at depth (using Anderson’s (1951) scheme); this is demonstrated in one case example (Streit, 2003 and Root et al., 2004 in Table 7.2). In this case example, $S_{h_{\min}} > S_V$ at a depth of 2.5 km indicates a changeover into a reverse fault regime, from a strike-slip fault regime at a depth of 1.5 km. The conjugate directions of shear failure change accordingly with a change of fault regime (compare Figures 7.12a and b); although, the $\Delta P$ required to reactivate the fault remains unchanged.

Lastly, predicting changes in the likelihood of fault reactivation as a result of varying the mean pore pressure gradient used for the base case (i.e. 10 MPa/km, Table 7.1) was considered difficult due to an absence of pore-pressure data. This parameter was not considered for sensitivity analysis.
7.5 Discussion

7.5.1 Fault interpretation and model

In this chapter, attention has been given to synthesizing the fault reactivation modelling of branch lines bearing in mind the fault-trace sinuosity/fault-plane curvature and fault tip. All features are known to potentially weaken the integrity of a fault trap, all forming part of trap complexity and; thus, relevant to the discussion. In addition, Lightenberg (2005) added fault plane roughness (rugosity) to the definition of fault complexity.

In this chapter, ΔPs have been estimated and compared either side of the branch line of master and splay faults; the effect of the splay fault on the likelihood of fault reactivation in a branched-fault case is subsequently assessed. Further, the differential strain, although not modelled is certain to also have a significant effect on whether a branch line acts as a potential fluid migration pathway (Gartrell et al., 2005; Gartrell and Lisk, 2005). Furthermore, even though the dilation tendency was shown to not be pronounced in the study area (Section 7.4.1), as a result of the high differential stress developed there, localised dilation tendency at branch lines may in fact have significance. By way of example, the dilation tendency of fault traps located on the North West Shelf was modelled (Gartrell et al., 2004; Ligtenberg, 2005). There, further modelling in Gartrell et al's (2004) study area was undertaken by Langhi et al. (2010) where localised hydrocarbon seepage was demonstrated in the vicinity of branch lines.

Figure 7.12. Sensitivity of the fracture stability (ΔP) attribute when varying the fault regime with depth. Major bounding master fault F55 is projected onto a stereogram. (a) Fault regime—strike-slip (S_{max}, S_V and S_{min}—42, 21 and 20 MP/km, respectively). (b) Fault regime—reverse (S_{max}, S_{min} and S_V—42, 22 and 20 MP/km, respectively). S_{min}—139°N. Reservoir depth—2.5 km.
The maximum fault-trace sinuosity/fault-plane curvature can be significant with strikes varying up to ± 33° in the study subarea (Chapter 3). The significance of this observation is that portions of the fault plane can have a low likelihood of fault reactivation that may otherwise be considered fairly susceptible to reactivation. Previous studies incorporating fault reactivation modelling, such as the Northern Gas Fields Route (Root et al., 2004; Root, 2005), Kingfish Field (van Ruth and Nelson, 2005; van Ruth et al., 2006) and Tuna–West Tuna Field case studies (Nelson et al., 2006a) did not incorporate detailed 3-D fault interpretations; thereby, making comparisons with this study of limited value.

Rugosity is important to consider as it can translate to an actual shear strength assigned to a fault that is different to that assumed in the modelling; if not accounted for, the fracture stability (ΔP) predictions can be expected to differ. It follows that fracture stability predictions are only an indicative measure of the likelihood of fault reactivation since the rugosity cannot be accounted for in detail, the latter also dependant on the host rock (Wibberley et al., 2008). In one case study, fault-surface roughness was found to vary with accumulated slip, where an order of magnitude increase in rugosity was noted for small-scale slip in comparison to large-scale slip (Sagy et al., 2007). However, 3-D high-resolution topography measurements, performed on two outcropping faults (in a separate study), did not corroborate this observation (Candela et al., 2009); and the authors instead, pointed to the fault growth mechanisms and/or fault branching as being potentially responsible for the fault-surface roughness.

Defining ‘true’ fault-surface rugosity is difficult. In this study, the fault-plane trimesh which defines the fault-plane curvature was computed using the unconstrained triangulation method in conjunction with a high-smoothing filter. Thus, fault-surface roughness was not identified. Nevertheless, localised artefacts still remain on some fault planes (e.g. Figures 7.8c–e), as is demonstrated when using the maximum curvature, minimum curvature and Gauss attributes to depict the fault-plane smoothness. These artefacts are known to be due to local mislocation of fault segments and, are excessively time consuming to fix since hundreds of fault segments exist for any one fault plane. Ultimately, a dilemma exists regarding what is an acceptable representation of fault-surface rugosity, bearing in mind seismic resolution limits (see Figure 3.5). In time, neural-network analysis in combination with seismic attributes will likely facilitate accurate detection and/or imaging of the fault-surface rugosity, as is already the case with detecting seismic anomalies along branch lines, where these are associated to fluid-escape conduits (Lightenberg, 2005). Failing this, the residual point-source artefacts are used in this chapter to illustrate their potential impact on the ΔP predicted. For example,
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a localised artefact can be seen adjacent to the intersection of faults F55 and F56 (Figure 7.8c); there, the \( \Delta P \) prediction clearly differs from the local trend across the fault plane.

The presence of fault tips extending into the seal intervals (i.e. as high as the SworSS interval) is shown in this study to be localised and, only across a few fault planes. In these localised zones, the trap-breath risk could be higher, although not demonstrated either way in this study. The presence of fluid migration pathways at fault tips is a well established mechanism for potentially causing trap failure (Gartrell et al., 2004; Gartrell et al., 2005). One mechanism via which this can occur is via dilational fault-tip propagation, as is inferred to occur on the North West Shelf (Cooper et al., 1998). With respect to this mechanism, the newly proposed evidence herein, suggests that most Mack faults arrest at the Mackerel Unconformity. Further, basin extension has been demonstrated to be ongoing herein only to the Mackerel Unconformity, but not beyond it, suggesting that fault tips may be less likely to propagate through dilation or crack-tip growth, as is inferred to occur on the North West Shelf (Cooper et al., 1998). This implies that any fault traps below the Mackerel Unconformity, and reliant on post Mackerel Unconformity seal, may be less likely to act as potential fluid-escape conduits. Other types of bypass systems such as is documented in other basins (Cartwright et al., 2007), are not observed.

7.5.2 Fault reactivation and fault-trap breach

Fault reactivation modelling studies in the Gippsland Basin include the Northern Gas Fields Route and Kingfish Field studies. For the Northern Gas Fields Route study, fault reactivation modelling was performed on 9 of the 30 faults interpreted, these nine having a throw of excess of 30 m (Root et al., 2004; Root, 2005). Further, only two failure envelopes were considered (\( C = 0, \mu = 0.6 \) and \( C = 0, \mu = 0.85 \)) in the modelling and, only the slip tendency attribute was used to predict the likelihood of fault reactivation. Ultimately, the likelihood of fault reactivation was estimated as intermediate to low (i.e. \( 0 < T_S < 0.6 \)) for seven of the nine faults and, high (\( T_S > 0.6 \)) for the remaining two faults (Streit, 2003; Root et al., 2004). The overall likelihood of fault reactivation in the Central Deep was, in parallel, estimated as intermediate to low (Root et al., 2004). These results are, however, of limited comparative value to the present study for a number of reasons. Firstly, the structural model used was only constrained by a 2-D seismic interpretation. Any localised variation in strike is therefore, only coarsely constrained, so that portions of faults with a potential low likelihood of reactivation were not detectable. Secondly, a \( S_{Hmax} \) of 130°N was used rather than the current best estimate of 139°N (Table 7.1), although as determined in this study, a 10° difference only changes results marginally. Thirdly, the \( \text{slip} \) and \( \text{fracture stability} \) attributes were not utilised as they were in this study.
In the case of the Kingfish Field study, fault reactivation modelling was carried out on 12 representative faults from the seismic 3-D cube (van Ruth and Nelson, 2005; van Ruth et al., 2006); secondary faults were not interpreted. High-angle NE–SW-trending faults were determined to have a low likelihood of reactivation and, low-angle faults a relatively high likelihood, as is found in this study. In addition, high-angle NNW–SSE and ENE–WSW-trending faults were found to have the highest likelihood of reactivation. Specifically, a minimum ΔP of 3.78 and 15.6 MPa were modelled for the cohesionless (C = 0, μ = 0.65) and intact/healed fault cases (C = 5.4, μ = 0.78), respectively. Also, the maximum ΔP (for the Latrobe Group) was modelled at 14.5 MPa for target reservoir depths of approximately 2.5 km. The conjugate directions of shear failure determined are near-identical to those estimated in this study; the result of the near identical in situ principal stresses used in both studies (see Table 7.1). However, although van Ruth and Nelson (2005) and van Ruth et al. (2006) estimate optimal azimuths that will induce fault reactivation, they do not provide stereograms showing poles-to-plane plots of individual faults. Again, neither of these two studies is directly comparable to this study, although this study mostly confirms their basic findings.

In this study, the comparative basis for associating ΔP to the likelihood of fault reactivation is qualitative, where low, moderate, or high likelihoods of fault reactivation equate to 9 < ΔP < 15 MPa, 15 ≤ ΔP < 20 MPa, or ΔP ≥ 20 MPa, respectively. In a manner similar, low, moderate, or high integrity traps, linked to drilled prospects in the Vulcan Sub-basin Northwest Australia, were defined by ΔP < 10 MPa, 10 ≤ ΔP ≤ 15 MPa, or ΔP > 15 MPa, respectively (Mildren et al., 2002b). In Mildrens’ study (op.cit), the lowest known hydrocarbon and lowest closing contour were compared against the ΔPs estimated along the fault traces. A broad correlation between the percentage of hydrocarbon fill in a trap and the likelihood of fault reactivation, as defined by ΔP, was established. In the latter case, the broad correlation is useful, but additional calibration constraints of ΔP to hydrocarbon fill would be required to make the correlation absolute, rather than relative. In the case of a second study, the likelihood of reactivation for faults from the Great Australian Bight Basin (off southern Australia) were examined using a scale of 1–20 MPa (Reynolds et al., 2005). In the latter case, no hydrocarbon accumulations were available to ground-truth ΔPs.

The estimates of C and μ are fundamental when estimating ΔPs and, associating these to a likelihood of fault reactivation. The argument focus is whether the cohesive strength of fault rocks, the cohesive strength of intact reservoir rock, or some combination is representative when assigning C in fault reactivation modelling. The cohesive strength of a fault rock is known to potentially exceed that of a reservoir rock (cf. 17 MPa versus ~4–8 MPa), in the case where fault gouge diagenesis has occurred (Dewhurst and Jones, 2003). A similar contrast in cohesive strength was also found, for
Chapter 7—Fault reactivation modelling

reservoir and fault rocks from the Otway Basin, although not across the full range of effective normal stresses being considered (Dewhurst et al., 2002). Finally, the competency contrast between the cohesive strength of the host and fault rocks is thought to be potentially responsible for concentrating stress at the host-to-fault rock boundary, where rock failure subsequently occurs (Dewhurst et al., 2005).

Following on from the above paragraph, one can also associate rock strength to lithology and/or diagenesis occurring in the reservoir. For example, an empirical association between lithology and rock strength has been substantiated in one case study that compared the angle of internal friction ($\Phi$) for different rock types to their respective GR response (Chang et al., 2006). As expected, compared to sandstones, shaly rocks have a lower internal strength. Regarding fault diagenesis, a petrology study undertaken to research the effects of CO$_2$ on the mineralogy of the Tuna Field reservoirs (Schacht, 2008b), demonstrated that diagenetic processes (compaction, solution–authigenesis, cementation and replacement) had taken place in both CO$_2$-rich and CO$_2$-poor reservoirs. Authigenic minerals and cements were demonstrated to be more common in the CO$_2$-rich reservoirs, where the authigenic mineral assemblage was estimated at 55% FeCO$_3$, 41% MgCO$_3$ and 4% CaCO$_3$ (Schacht, 2008a). These petrology results, when compared with the average percentages estimated for key lithologies in this study (81% sandstone, 10% shale and 9% other) suggest that fault rocks would be hard, should they be present. If diagenesis has occurred within the fault plane, the cohesive strength of fault rocks could possibly exceed that of the reservoir rock. Nevertheless, it must also be appreciated that irrespective of how $C$ and $\mu$ are estimated they remain poorly constrained in this study.

Ultimately, predicting the likelihood of fault reactivation still remains a relative estimation, irrespective of how consistently the modelling has been carried out. Ideally, the modelling would benefit by comparing the likelihood of fault reactivation against drilled fault traps that hold accumulations.

7.4 Conclusions

The fault reactivation modelling indicates that 21% of the 62 faults can sustain a $\Delta P$ in excess of 25 MPa and 79% of faults a $\Delta P$ of between 10 and 25 MPa, before reactivation is likely to occur when considering the intact/healed rock case ($C = 2$ MPa, $\mu = 0.75$). For cohesionless fault failure, the $\Delta P$ calculated is 9.33 MPa less. No obvious trends emerged for the 62 faults modelled using the slip tendency attribute, but the dilation attribute suggests that, because of the high differential stress estimated across the study subarea ($\sim 22$ MPa), tensile failure is unlikely.
The overall likelihood of reactivation, for both stand-alone and branched faults, is high. Further, the likelihood of reactivation is high to moderate for key branch lines (e.g. F55–F56; sublead 2d), stand-alone faults in the West Tuna and Tuna Fields (subleads 2a–2b) and for the F55–F19 branch line (sublead 3b). However, the likelihood of reactivation for some stand-alone faults can be low to moderate, but only across localised portions of the fault plane (e.g. F13, F18, F20 and F56). Irrespective of the modelling, faults F55 and F19 and their associated splay faults, bound the northern edge of a known fault-bounded hydrocarbon accumulation (Kipper Field), thereby, establishing that fault traps can seal. The likelihood of fault reactivation in multibranched fault traps, increased for 32% of cases and decreased for 26% of cases as a result of introducing splay faults; there being negligible to no change for the remaining 42% of cases. It follows that splay faults (many having only minor throw) should nevertheless be considered in CO2SL assessments, especially in cases where branched fault traps are probable or definite.

The NE–SW-trending faults (F91, F151 and F165) bounding the western limb of the Tuna–West Tuna Field structures have a low likelihood of reactivation; the maximum ΔP magnitude calculated for the intact/healed case (C = 2, μ = 0.75) is ~70 MPa for F91. Furthermore, the ΔPs modelled across branch lines for these three faults ranges from 17–48 MPa. Thus, the Tuna–West Tuna Field structures, together with the Flounder Field and Pilotfish-1 structures (located to the south), are considered good potential candidates for CO2 storage, when considering ΔP alone.

Minor variations to SHmax, Shmin and SV have an equally marginal effect on the calculated ΔP. Similarly, varying SHmax by 10° has a marginal effect on ΔP (within the likely Stdev range). The majority of faults have elongated sinuous fault traces, and the strike can vary by up to ±33°. The ΔP range required to reactivate such faults is commensurately broad, resulting in localised areas along the fault planes having a low likelihood of fault reactivation, and thus, providing potentially, localised traps for CO2 storage with the breach-of-trap risk anticipated to be lessened, when considering ΔP alone.
CHAPTER 8—CONCLUSIONS

Summarising the workflow program, the basin’s regional fault systems and unconformities were first reviewed (Chapter 2). A 3-D seismic interpretation was then undertaken to ascertain the fault geometry and geohistory; the fault strike, dip and mode were interpreted, fault-throw and province/subprovince families defined, and the upper tip-line bound for all faults determined (Chapter 3). Seismic TWT profiles and variance-attribute slices, in combination with age-depth plots, were then used to interpret the fault chronology and unconformities, both regional and local. The structure was initially interpreted in the time domain and, subsequently, depth converted using the Witosoft© software (Chapter 4). Then, CO2SLs were identified and a study subarea defined encompassing the top three screened CO2SLs (Chapter 5). The status of fault-seal integrity, at the scale of a CO2SL, was determined by assessing key uncertainties involved with the reservoir–seal intervals juxtaposed across-fault, and modelling shale smear across the fault plane (Chapter 6). In the process, the interpretation of branch lines was refined. Finally, the likelihood of fault reactivation was modelled, in particular, concentrating on the branch lines where these involve minor faults, many splay faults (Chapter 7).

In meeting the study’s research objectives, new insights have been gained regarding the structural geology of the study area. An assessment of the study area’s CO2 storage potential was undertaken and lastly, a new depth-conversion software was developed, as expanded on below.

(i) New intra-Halibut Subgroup unconformities (ILHalS, LHalSS and IUHalS) have been identified that, in conjunction with the interpreted fault patterns, better constrain the fault chronology.

(ii) The 2-D depth-conversion Witosoft© software was upgraded to allow the functionality of depth-converting a 3-D SEGY cube, in addition to the horizons and faults interpreted (ASCII format). The software was trialed using this study’s time-domain SEGY cube and interpretation, in partnership with W. Seweryn of PIRSA who developed and tested the program. The accuracy of the depth conversion achieved, shows absolute depths with a RMS error of ± 17 m, (at 1 Stdev) and, ± 27 m (at 2 Stdev). In comparison, the RMS error for relative depth is inferred to be less, and only marginally more than the digital sample spacing of 5 m—the accuracy achieved was considered adequate for determining relative depth offsets across faults.

(iii) Structure-based criteria, newly introduced in this study, were used to identify and screen 12 CO2SLs and 40 subleads located in the study area. These criteria include the flow-path distance, flow-path height and sweep area of a sublead. Other criteria taken into account
include the fault-trap type, depth to reservoir and complexity of the fault arrays. Average flow-path distances and flow-path heights can be as high as $7.4 \pm 4.2$ km and $0.55 \pm 0.14$ km, respectively, depending on the seismic horizon being considered. The flow-path azimuths determined from structural gradients mostly bear to the northwest. The sweep areas estimated for the subleads can be considerable, ranging from less than 1 km$^2$ and up to 32 km$^2$ (excluding merged subleads and, the intra-channel traps at CO$_2$SL-12a and b, where sweep areas are estimated at 38 and 153 km$^2$). Faulted rollovers, faulted subcrops and fault traps are common throughout the lower Halibut Subgroup section; while pinchout edges, rollovers and subcrops are prevalent in the upper Halibut Subgroup section.

(iv) Favourable reservoir intervals for CO$_2$ injection, from most to least attractive are the upper Halibut Subgroup (UHalSS1–UHalSS2), the lower Halibut Subgroup (LHalSS1–LHalSS2) and Golden Beach Subgroup (GBeaSS). The sand-to-shale ratios for the UHalSS1–UHalSS2 intervals are high, such that sand-on-sand windows dominate across-fault. In comparison, the sand-to-shale ratio in the Golden Beach Subgroup is lower so that sand-on-shale windows are inferred to be more likely across-fault. Also, the petroleum-bearing fault traps, in the Golden Beach Subgroup at the Kipper Field structure, prove that seal integrity across-fault can be effective.

(v) The depth to the reservoir interval varies from 1.1 km at the IUHalS horizon (e.g. CO$_2$SL-9b) to 5.1 km at the SeahSS horizon (e.g. CO$_2$SL-7g). The top-three screened CO$_2$SLs have depths to reservoir ranging from 1.4 km at the LatrSS horizon to 4 km at the LHalSS horizon, all within porosity-preservation depths.

(vi) This study represents the first structural interpretation to incorporate a fault seal analysis for CO$_2$SLs. Prior to this study, to the author’s knowledge, no juxtaposition analysis and modelling of shale smear had been undertaken in the Gippsland Basin.

Conclusions from this study’s research are set out below.

**Structural interpretation, faulting events, basin phases and fill history:** Although the Gippsland Basin is, in detail more tectonically complex, it can nevertheless be tectonically classified as the failed arm of a triple junction, which has many of the characteristics of a rift basin and Atlantic type rift margin (Le Pichon and Sibuet, 1981). As such, the structure-based conclusions that follow, originate from broad-scale observations, deduced from the structural interpretation of the whole study area—how they relate to the fault-trap integrity within CO$_2$SLs is discussed.
Firstly, the syn-rift–transition-rift basin phase and fill (associated with the Emperor–Golden Beach Subgroups) is postulated to be less attractive for \( \text{CO}_2 \) storage than the rift-drift–inversion basin phase and fill (of the Halibut Subgroup). This conclusion is, in part, due to the higher density fault network anticipated in across fault-block complexes within the Golden Beach Subgroup section. The existence of the fault network is, in part, inferred from the unclustered distribution observed from strikes plotted on stereonets for the Seah faults interpreted across the Northern Strzelecki Terrace. This conclusion is also substantiated by Power (2003) who observed that the fault spacing in the Golden Beach Subgroup section is further diminished by structural events after the deposition of this section. Power (2003) shows that closely-spaced fault blocks are present, where dimensions of 3–27 km in the Santonian–Campanian drop to 2–10 km in the Maastrichtian. By comparison, the fault network across fault-block complexes in the Halibut-Subgroup section is implied to be reduced; as shown from the more clustered distribution of the strike assigned to Mack faults, relative to that of Seah faults. This change in the fault spacing across these subgroups is attributed to a 45° rotation of the maximum principal stress \( \sigma_1 \), with \( S_{\text{Hmax}} \) varying from E–W in the Campanian to NW–SE in the Palaeocene–Early Eocene (Power, 2003; Power et al., 2003). Ultimately, the higher density fault network and subsequent increase in compartmentalisation translates to a smaller aquifer–reservoir system. A smaller aquifer–reservoir system has been demonstrated to reduce \( \text{CO}_2 \) injection rates as a result of the relatively rapid pressure buildup caused by the system being more limited in extent (Cinar et al., 2007).

Secondly, in this study, the Seah faults are interpreted as being reactivated intermittently up to the Late Maastrichtian, with faulting waning during the Palaeocene, but then peaking during the Early Eocene (Mack faults). The interpretation is based, in part, on unconformities identified in this study (ILHalS, LHalSS and IUHalS), on the upper tip-line bound, as well as where, and when, changes in the fault mode occur. This new fault chronology provides an explanation for the occurrence of near-synchronous, but differing fault modes being present (normal, reverse and strike-slip), as well as the uplift and erosion resulting in the Mackerel Unconformity. Some degree of kinematic linkage between the Seah and Mack faults is likely, hydraulic communication probable, although the latter has not been conclusively demonstrated in this study.

Thirdly, in association with the synchronous fault modes mentioned above, an extensional tectonic regime dominated in the Palaeocene–Early Eocene, with peak faulting intensity occurring in the Early Eocene and associated with a compression regime. Uplift and erosion occurred coevally with the reverse faulting and associated inversion (or formed via transpression) structures interpreted on the western edge of the Flounder and Tuna/West Tuna Fields. In the Flounder Field, NE–SW-
trending inversion structures and reverse faults are interpreted to be offset by WNW–ESE-trending faults, which together form a flower structure. East of the Tuna Field, localised transpressional and transtensional small scale structures (or jogs) developed subparallel to the Rosedale Fault, together forming multibranch en echelon fault arrays. However, there is insufficient evidence to invoke a strike-slip regime; which is in agreement with the conclusion reached by Power (2003) and Power et al. (2003). In addition, intermittent short-offset strike-slip movements of the Rosedale Fault System may have occurred from the Miocene onwards; in part, corroborated by the contemporary state of stress estimated as borderline compression–strike-slip (Nelson et al., 2006b). The ramifications of the above is that the evidence brought forward from the structural interpretation helps corroborate the state of stress as determined from geomechanical interpretations; ultimately, strengthening the arguments resulting from the fault reactivation modelling, which is heavily dependant on correctly assigning the state of stress and regime.

Fourthly, fault zones and structural hinges were also interpreted, as these may represent areas where a potential breach-of-trap may occur. Commensurately, the SRFZ is interpreted as a fault zone; together with an area parallel and downdip of the Rosedale Fault. Two other possible fault zones are interpreted, on the western limbs of the Flounder and Tuna Field structures; these fault zones also coincide with the location of intersecting and differing fault modes (normal, reverse and strike-slip). The associated fault-zone widths are estimated using the relationship established by Wibberley et al. (2008), and range from 0.1 to 30 m (based on fault throws of up to 200 m established in the study area). If these fault zones are present, then the fault-zone widths are below the lateral resolution of the seismic data (i.e. Fresnel Zone width = 200 m for an average reservoir depth of 2,500 m). Following on from the above, structural hinges are interpreted below the SRFZ, Rosedale Fault and under the Turrum and Flounder Fields. Any flexure over structural hinges could induce fracturing in the overlying reservoir and seal intervals and, consequently, CO₂SLs 4, 9a, 9c, 9d, and 10 are downgraded by this perceived risk.

Lastly, of the faults analysed in the study area, 67% of faults arrest at the Mackerel Unconformity (Mack faults)—this unconformity is demonstrated, in this study, to be a major tectonic boundary in contrast to previous interpretations where the Latrobe Unconformity is taken as the dominant tectonic boundary (Holdgate et al., 2003a). Also, the Mackerel Unconformity surface is coincident with the upper bound of the main reservoir interval, represented by the Halibut Subgroup section, but stratigraphically and immediately below the intraformational/local seals represented by the Flounder Formation, Cobia Subgroup and Swordfish-Formation sections. The ramifications of the fault-tip statistics in relation to the breach-of-trap risk are as follows.
(i) The Mack faults present in the thicker sedimentary section (south of the SRFZ) have not been subject to significant reactivation post-Early Eocene, which has positive implications for fault trap/seal integrity. For example, no kinematic linkage was found between Mack faults contained within the Latrobe Group reservoir intervals, and Swor and Cong faults contained within the regional seal represented by the Swordfish and Conger Formations. The overall conclusion of this study is that the Swor and Cong faults do not pose a breach-of-trap risk in the study area.

(ii) The likelihood of crack-tip propagation ahead of the fault tip is anticipated to be minor. It follows that the likelihood of traps being breached is lessened, as a higher pore pressure can be sustained during CO$_2$ injection than would otherwise be the case where the upper tip-line bound is less convincingly constrained. However, this conclusion requires further modelling to be conclusively demonstrated.

**Juxtaposition analysis and shale-smear modelling:** Modelling of the $V_{\text{shale}}$ attribute for all faults indicates that it is unlikely that sand-on-shale windows can be maintained along fault-strike lengths that range up to 20 km. Average sandstone and shale percentages for the 11 wells modelled are estimated at 81% sandstone, 10% shale and 9% for other lithologies. Further, modelling of the SGR attribute indicates that ~15% of fault planes have a SGR < 0.15, ~60% a SGR of between 0.15 and 0.25 and ~25% a SGR > 0.25. These SGR attribute percentages suggest that sealing across-fault by shale smear is possible, subject to shale being entrained in the fault zone and, it being continuous across the fault plane. However, first-pass estimates of CO$_2$ column heights potentially retainable by shale smear-based seals (i.e. 8.6–100% of the trap fill), were inconclusive, suggesting more detailed models need to be built. Petroleum-bearing reservoirs, present in fault-traps at the Longtom and Kipper Fields, demonstrate that localised sealing across-fault is effective (Sloan et al., 1992; Lanigan et al., 2007); however, it is uncertain whether trapping and/or sealing is established by sand-on-shale windows suitably juxtaposed across-fault or, in part, by the occurrence of shale smear. Finally, it is reasonable to infer that the wells located basinward of the study subarea (e.g. Flounder Field), and therefore closer to the basin depocentre, will intersect greater shale percentages. It follows that more sand-on-shale windows across-fault are expected for CO$_2$SLs located adjacent to the basin depocentre (e.g. CO$_2$SL-4).

**Fault reactivation modelling:** The overall likelihood of fault reactivation for both stand-alone and branched faults is interpreted to be high to intermediate, although there are localised portions of the fault planes where it is considered low. A low likelihood of fault reactivation, estimated across portions of the fault plane, is partly due to the fault strike varying by up to $\pm 33^\circ$. When considering all faults, the fault reactivation modelling indicates that 21% of the 62 faults can sustain a $\Delta P$ in
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excess of 25 MPa and 79% of faults a $\Delta P$ of between 10 and 25 MPa, before reactivation is likely to occur when considering the intact/healed rock case ($C = 2$ MPa, $\mu = 0.75$). The cohesive strength was substantiated, in a large part, from thickness percentages of the lithology, as petrophysically estimated from well logs.

The likelihood of fault reactivation can also be inferred by considering the branch lines of fault arrays, the latter consisting of master and splay faults. It was found that the likelihood of fault reactivation increased for 32% of the branch-line cases considered, and reduced for 26% of the branch-line cases; with the change being minimal for the remaining 42%. It is concluded that splay faults, many of them minor faults, need to be included in CO$_2$SL assessments to fully assess a fault trap’s integrity. It was found that the NE–SW-trending faults (F91, F151 and F165) bounding the Tuna and West-Tuna Field structures have the lowest likelihood of fault reactivation; there, maximum $\Delta P$ magnitudes of 70 MPa can be sustained for the intact/healed fault case. However elsewhere, the maximum $\Delta P$ magnitudes that can be sustained is reduced in the case of branched faults; being in the range of 17–48 MPa.

The mean fault strike, for the majority of faults, ranges from 095° to 140°N; these strikes are parallel/subparallel to one of the conjugate planes of shear failure so that many faults are susceptible to fault reactivation. It has been established that the effect of varying $S_{h\text{max}}$, $S_{h\text{min}}$ and $S_v$ in the modelling of $\Delta P$ is marginal (within their estimated standard deviation range). Similarly, varying $S_{h\text{max}}$ by +10° did not affect the outcome. However, overall the tortuosity/sinuosity of the fault plane/fault trace (i.e. ± 33°) has been found to be a more influential factor than the above, when considering the likelihood of fault reactivation alone. The latter conclusion further emphasises the need to interpret fault curvature using 3-D seismic datasets.

**Recommendations:** Research opportunities stem from the outcomes of this study, as follows.

(i) The economic viability of CO$_2$ storage is contingent on the reservoir–aquifer system being extensive (Cinar et al., 2009), also mentioned to by Economides and Ehlig-Economides (2009). This is partly due to high injection rates being more difficult to achieve with increased compartmentalisation (Cinar et al., 2007), irrespective of whether the compartmentalisation is stratigraphic or structural in origin. Demonstrating the impact of compartmentalisation by varying the spacing and/or density of the fault network across fault-block complexes (through reservoir simulation studies) would help establish the economic viability of a CO$_2$ storage project. Further, it is anticipated that the transmissivity multipliers assigned to the faults would be varied as part of the accompanying sensitivity analysis.
(ii) The fault seal analysis in this study modelled the effect of inclusion of both major and minor faults on a CO₂SL, but did not include subseismic faults. Ideally, subseismic faults would need to be modelled to further understand the effect on CO₂ injection rates by introducing increasingly more subtle structural features. However, subseismic faults are difficult to predict, although methodologies incorporating the use of the seismic curvature attribute (Chopra and Marfurt, 2005, 2007), or geomechanical modelling, show promise. For example, the application of the curvature attribute to structure-based interpretations of CO₂ storage sites was demonstrated in carbonate-reservoir intervals where subtle fracture trends were identified (Nissen et al., 2009). Alternatively, geomechanical modelling gave encouraging, statistically meaningful results in North Sea basins (Maerten et al., 2006; Maerten and Maerten, 2006).

(iii) The majority of faults in the study area have been shown to arrest at the Mackerel Unconformity; however, subtly varying the upper tip-line bound to assess its effect on trap integrity was not modelled. The latter is important because of the fault tip’s known association with fluid-flow pathways (Gartrell et al., 2004); for example, through crack-tip propagation (Kranz, 1983; Bourne and Willemse, 2001). Hence, it is recommended that the dependency of a trap’s integrity on alternate sealing options, at the upper tip-line bound, be investigated. It is proposed that alternate sealing options could be first established using fault-seal-analysis software and, any effects modelled by reservoir-simulation software. Such modelling could subsequently be supplemented by analysing seismic attributes across a 3-D seismic dataset to establish the presence, or absence, of gas chimneys so as to, in part, verify the reservoir simulation predictions. By way of a recent example, preliminary investigations of gas chimneys were undertaken in the near offshore part of the Gippsland Basin using seismic attributes (Nourollah et al., 2010).

(iv) A 3-D geomodel would need to be built to fully capture the status of juxtaposition and shale smear-based sealing at the individual reservoir scale. However, because of the particular sensitivity of the Vshale and SGR patterns to the well-control and distribution, as established in this study, geostatistical methods would need to be used in order to critically capture and assess the full range of the projected attributes.
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