Chapter 5

Eumeralla Seals in a Sequence Stratigraphic Framework

5. EUMERALLA SEALS IN A SEQUENCE STRATIGRAPHIC FRAMEWORK

5.1 Rift Lake Evolution

Rift lake evolution is a function of tectonics and climate (Bohacs 2002). Subsidence rate is the primary control on lake development with the deepest lakes occurring at maximum subsidence rate, however, climate controls what type of lake occurs at maximum subsidence (Bohacs 2002). Carroll and Bohacs (1999) recognised three major facies associations in lake strata based on observations of lake systems of Cambrian to Recent age; fluvial-lacustrine (progradational stacking of mostly clastics), fluctuating-profundal (progradation and aggradation of chemical and clastic sediments), and evaporitic (mostly aggradation of significant amounts of chemical sediments). These facies are associated with three different lake basin types, overfilled, balanced-fill and underfilled lake basins, dependent on the relationship between potential accommodation and sediment plus water influx (Fig. 5.1) (Bohacs et al. 2000).

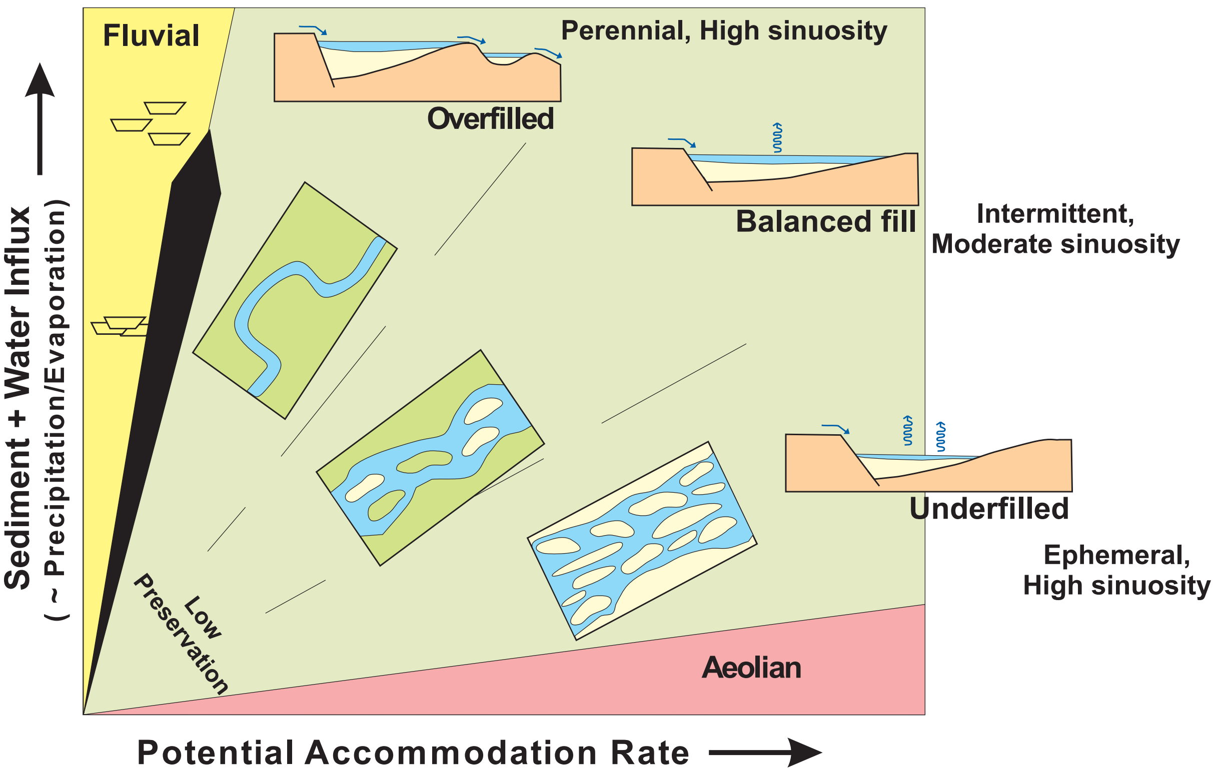


Figure 5.1 Lake basin types and associated fluvial styles as a function of sediment + water influx and potential accommodation rate. Modified from Bohacs (2002).

Seismic studies indicate that the structural evolution of the Otway Basin is analogous to basins such as the Tucano-Reconcavo Basin of Brazil and the Gabon and Cabinda Basins of the west coast of Africa (Aburas & Boult 2001). Within the Reconcavo Basin, balanced-fill lake basin type dominated during peak rifting (Bohacs 2002). This was followed by overfilled lake basin type conditions during the rift to sag transition, whereas fluvial conditions dominated during a late sag phase (Bohacs 2002).

With an equivalent evolution in the Otway Basin, the syn-rift Laira Formation within the Crayfish Group is likely to represent balanced-fill conditions. Balanced-fill lake basins commonly develop where there is a wet climate at maximum subsidence, and the rates of potential accommodation and sediment plus water supply are roughly in balance (Fig. 5.1) (Bohacs 2002). This lake basin type contains the most prolific lacustrine source rocks and beneficent facies juxtapositions for hydrocarbon accumulations (Bohacs 2002).

The sediments of the lower Eumeralla Formation were deposited in a late rift to early sag phase (Fig. 1.2), when subsidence rates would have been much lower than during the main rifting event. With the rate of sediment plus water supply exceeding potential accommodation, an overfilled lake basin type is likely to have developed (Fig. 5.1). This usually occurs when the precipitation-to-evaporation rate is relatively high or the rate of tectonic subsidence is relatively low (Bohacs et al. 2000). Overfilled lake basin parasequences typically accumulate in humid, open-hydrology systems and consist of numerous asymmetric shoaling-upward stratal packages about 1-10 meters thick (Bohacs 2002). The distal lake environments are dominated by laminated, relatively organic-rich shales and mudstones (Bohacs 2002). These lithologies dominate within Eumeralla Formation Unit VI. The lowlands around the lake are typically covered by vegetation and accumulate peats, whereas small rivers traverse the upper lake plain depositing thin, fining-upward sandstones occasionally capped by coal (Bohacs 2002). Coals are most commonly associated with overfilled lakes, and the shales and mudstones are interbedded with both coals and fluvial deposits (Bohacs et al. 2000). This commonly occurs within the very variable sediments of Eumeralla Formation Unit V. Terrigenous organic matter from forests and mires occurs throughout the lake, increasing towards the shoreline, and typically contributes to mixed Type I (algal) and Type III (terrigenous) kerogens (Bohacs 2002). Carbonaceous material is common within both Unit VI and Unit V sediments. The preferential orientation of organic material parallel to bedding within Unit VI probably reflects the distal, quiet conditions within this interval, in contrast to the more proximal, higher-energy conditions giving a more random orientation of organic material within Unit V sediments.

Analogue data suggest that fluvial conditions commonly dominate in a late sag phase (Bohacs 2002). The thickness of the Eumeralla Formation Unit II sequence, as wells as its relatively coarse grain size (Fig. 4.7), suggests that sedimentation rates were high in a late sag phase within the Otway Basin. A very high sediment plus water influx relative to accommodation resulted in a fluvial-dominated and sand-rich upper Eumeralla Formation (Fig. 5.1). Thin coal beds and organic material is present throughout the Eumeralla Formation, however, the high sedimentation rates within the upper parts of the formation limited peat growth and development of coals here.

Bohacs (2002) suggests that the various lake basin types are also associated with different fluvial styles (Fig. 5.1) (Bohacs 2002). The high sedimentation rates and low accommodation characteristic of overfilled lake basins typically give perennial, high sinuosity fluvial systems, whereas fluvial systems within balanced-fill lake basins have more moderate sinuosity (Bohacs 2002). This theory implies that the lower Eumeralla Formation may have been deposited within a fluvial environment of higher sinuosity than the Laira Formation sediments. Some authors (O'Brien et al. 1994; Perincek et al. 1994) suggest that the Eumeralla Formation was deposited by a sluggish, meandering river system resulting in fine-grained, poor reservoir quality sandstones, in contrast to the high-energy, braided system of the Crayfish Group. However, Duddy (1983, 1997) suggests that the Eumeralla Formation was also deposited by a high-energy fluvial system, with well-developed coarse-grained channel sandstones (>40 per cent primary porosity) occurring within finer-grained floodplain deposits. Duddy (1983, 1997) argues that early and pervasive diagenesis of the volcanogenic detritus caused massive destruction of the permeability and porosity under only moderate burial of about 1 to 2 km, thereby producing the illusion that this was a low-energy environment. The understanding of Eumeralla Formation sequence stratigraphy and fluvial styles developed through this study agrees with elements of both of the above theories. The lower Eumeralla Formation was deposited within a high sinuosity fluvial system, as proposed by O'Brien et al. (1994) and Perincek et al. (1994), while the upper Eumeralla was deposited in a high-energy fluvial system, as suggested by Duddy (1983, 1997).

5.2 Eumeralla Formation Systems Tracts

The Crayfish Unconformity represents the main sequence boundary, and marks a period of negative accommodation following tectonic uplift and erosion of the Crayfish Group sediments. The Windermere Sandstone Member was deposited as an aggradational lowstand systems tract on top of the unconformity. The low accommodation space associated with lowstand systems tracts commonly results in considerable reworking of the channel belts and laterally extensive sands (Lang et al. 2002a). Development of incised valleys caused local thickening of the sands, as observed on Windermere isopach map (Fig. 5.2) (Boult & Alexander 2002).

The Eumeralla Formation Unit VI represents a transgressive to early highstand systems tract, and the presence of massive claystones at the bottom of this interval suggests initial subsidence was relatively rapid (Figs 4.7, 5.3). The phase of deepest lake development represents the maximum flooding surface, and marks a transition into the early highstand of

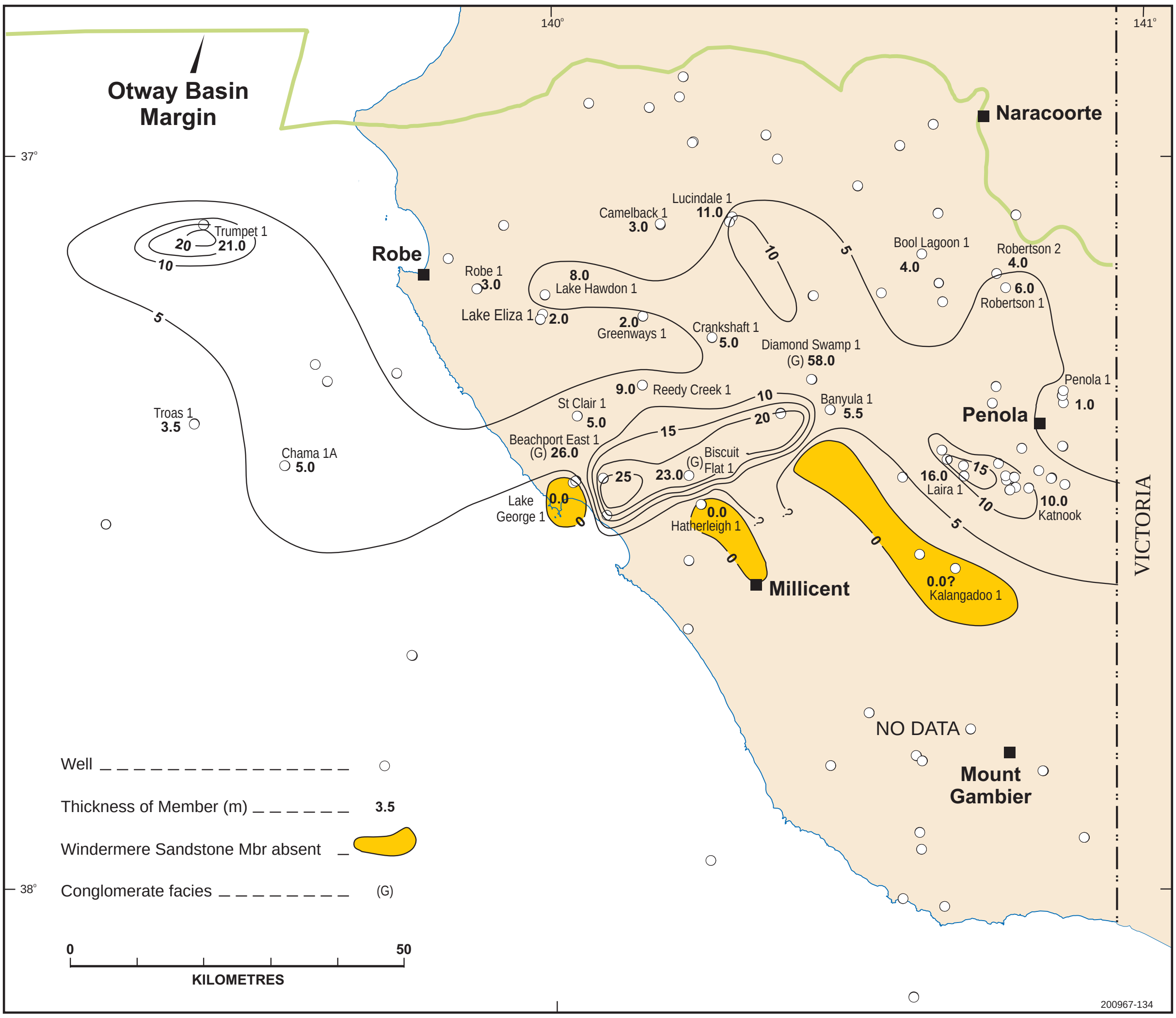


Figure 5.2 Isopach map of the Windermere Sandstone Member (Boult & Alexander 2002).

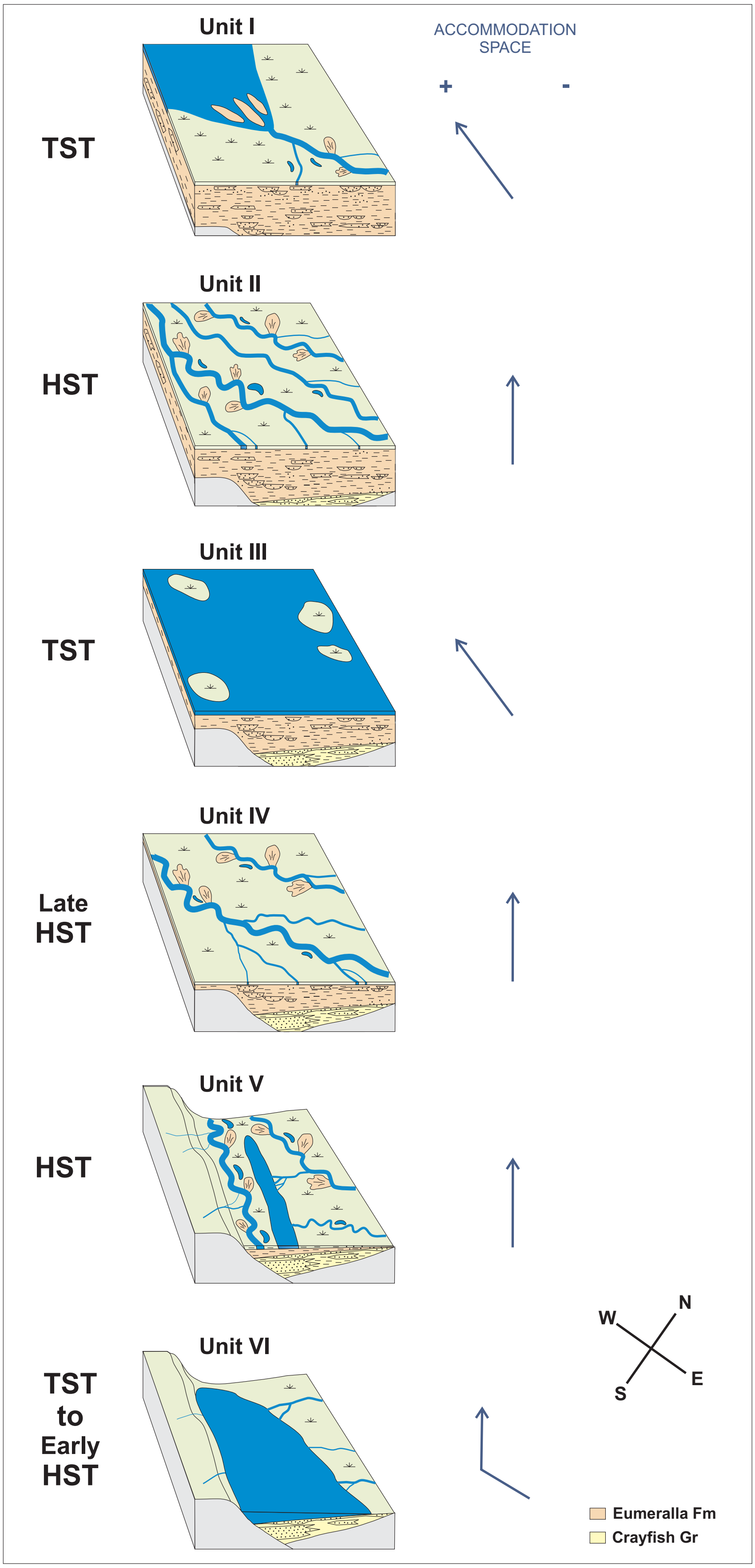


Figure 5.3 Depositional models and systems tracts of the Eumeralla Formation. Main drainage direction is towards the west. No scale is implied.

the upper Unit VI, the highstand of Unit V and the late highstand of Unit IV (Fig. 5.3). This change follows an increase in sediment influx as the river system adjusts to the changes in base level. The fluvial channel belt is likely to have started migrating laterally due to the differential subsidence within the half grabens. Small lakes gradually filled in with sediments, until the main fluvial channel belt occupied the zone of maximum subsidence along the footwall block. Fluvial channel sands thereby overlie shallow lacustrine siltstones from the lower Unit V, while coals are associated with small lakes on the floodplain.

With a palaeo-latitude of 65-70˚ in mid-Jurassic to mid-Cretaceous (Frakes 1988), evaporation rates were likely to be low. The cool temperate Ob River Basin of Western Siberia as described by Lang et al. (2002a) may provide a modern depositional analogue to Unit V. Here, high sinuosity meandering channels occur within wide floodplains, and sedimentation rates on the floodplains are low enough to allow accumulation of peats and organic silts within abandoned channels (Fig. 5.4).

Sedimentation rates were most likely higher during deposition of the floodplain-dominated sediments of Unit IV. Only traces to very minor coals are present within this interval, suggesting conditions for peat growth were poor (Fig. 5.1).

Continued subsidence associated with mid-Albian faulting resulted in flooding of large parts of the floodplains and a transition to shallow lacustrine conditions. The sediments of Unit III were deposited as a transgressive package (Fig. 5.3), and their upper boundary represents a second maximum flooding surface. The overlying floodplain sediments of Unit II were deposited in a highstand systems tract. Marine influence towards the top of the estuarine Unit I suggests deposition during a transgressive event (Fig. 5.3).

5.3 Seals and Systems Tracts

Non-marine sealing facies are commonly associated with oxbow lakes and abandoned channel fills, lacustrine muds, and floodplain muds and silts (Lang et al. 2002a). Analogue studies from a range of different depositional environments indicate that lacustrine deposits generally provide laterally more extensive seals than fluvial overbank deposits (Fig. 5.5) (Lang et al. 2002b). However, seal geometry is also strongly influenced by the stratigraphic position of the seal facies (Lang et al. 2002b). Within overfilled lake basins, seal facies tend to be best and most extensively developed in distal transgressive and highstand prodelta strata

Figure 5.4 The Ob River Basin of Western Siberia may provide a modern depositional analogue to Eumeralla Formation Unit V. Wide floodplains are developed and incised abandoned channels are filled with silty sands and peats. Photo courtesy of Lang et al. (2002b).

(Bohacs et al. 2000). Seal-prone facies within balanced-fill lake basins are widespread and well developed in late transgressive and early highstand systems tracts (Bohacs et al. 2000). The retrogradational stacking pattern within transgressive systems tracts generally provides thicker and more laterally continuous lacustrine deposits than those commonly found in highstand systems tracts (Lang et al. 2002a). The thickest seals are found where subsidence is fast, thereby limiting the time when the sediments are available for erosion and ensuring preservation of the seal facies (Lang et al. 2002b). The sediments must also be deposited distal enough to limit clastic input (Lang et al. 2002b).

The distal, lacustrine sediments of Eumeralla Formation Unit VI were deposited in a transgressive to early highstand systems tract during relatively fast subsidence, resulting in the potential occurrence of a very good and preserved sealing facies near the base of the formation. Mapping of Unit VI showed that the interval is not laterally extensive within the St Clair Trough, as it cannot be correlated between wells located 11km apart (Fig. 4.24). The

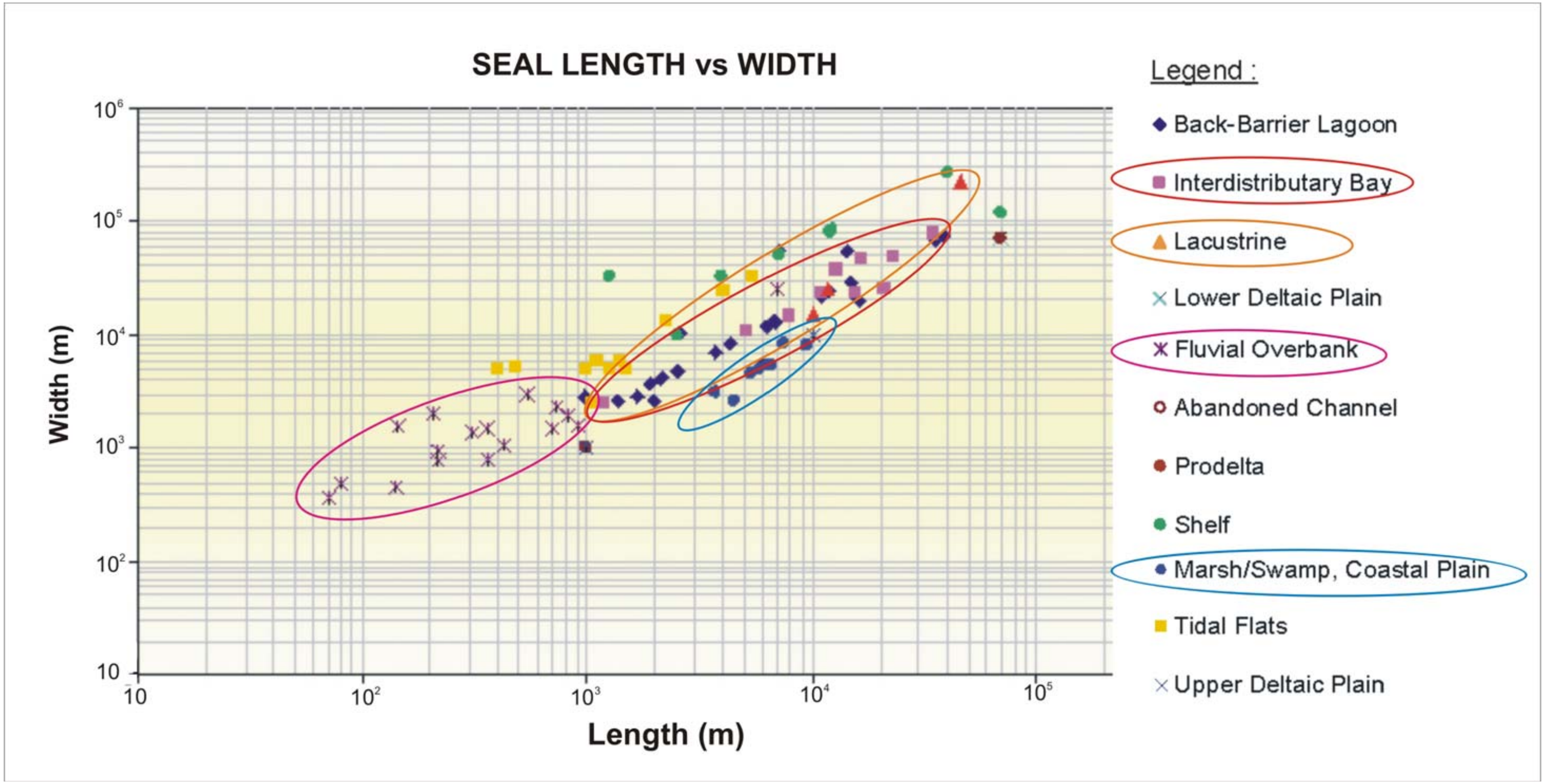


Figure 5.5 Seal width versus seal length for various depositional environments based on analogue data (Lang et al. 2002b).

limited distribution is likely to be a result of its deposition in a rift to sag transition. Thick and extensive lacustrine shales typically occur within the syn-rift sequence and associated with balanced-fill lake basins, whereas mature fluvial sandstones often dominate within the post-rift sequence (Bohacs 2002). The subsidence rate during Eumeralla Formation deposition was not high enough to allow the development of very deep and extensive lake environments.

Unit VI provides greater thicknesses of excellent sealing lithology than the highstand lacustrine Unit V, and is less variable. Minor sandstones occurring within the transgressive systems tract are likely to be surrounded by fine-grained, low-permeability sediments and not be interconnected. Highstand coals and floodplain deposits have highly variable lateral connectivity (Lang et al. 2002a), reducing the likelihood of an extensive seal to be present within the floodplain-dominated parts of Unit V and also Unit IV.

Despite the occurrence of Unit III within a transgressive systems tract, the influx of relatively coarse-grained clastics is too high for any thick and extensive sealing facies to be developed here. The lake environment is very shallow and strongly influenced by fluvial processes. Within Unit II, the very low accommodation rate relative to sediment supply is likely to give amalgamated fluvial channel deposits and poorly developed sealing facies (Fig. 5.6) (Bohacs 2002). Channel stacking is independent of river type and changes by non-unique pathways in response to minor changes in sedimentation relative to accommodation (Fig. 5.6) (Bohacs 2002). In general, however, the relationship between sedimentation and accommodation throughout the Otway Basin rift to sag transition versus the late sag phase suggests that amalgamated fluvial stacking patterns are better developed within the upper Eumeralla Formation.

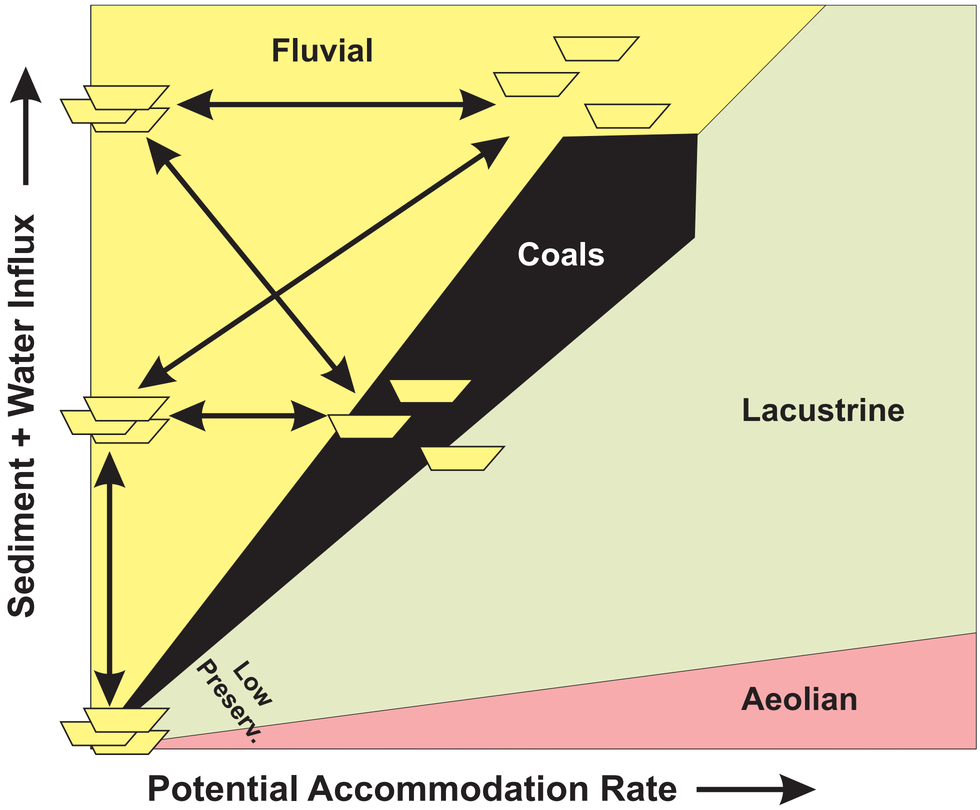


Figure 5.6 Fluvial stacking is independent of river type and is a function of accommodation versus sediment supply (Bohacs 2002).

Chapter 6

Eumeralla Formation Seal Potential

6. EUMERALLA FORMATION SEAL POTENTIAL

6.1 Introduction

A seal is defined as any rock that impedes the movement of hydrocarbons (Downey 1984, Kaldi & Atkinson 1997, Vavra et al. 1992). Theoretically, any lithology may form a top seal to a static hydrocarbon column as long as the capillary forces within that sequence act to confine the buoyancy forces of accumulated hydrocarbons (Jones et al. 2000). For a top seal to be effective, however, it needs to be relatively thick, laterally continuous, homogeneous and fairly ductile (Downey 1984). Top seals can be divided genetically into those that fail by capillary leakage (membrane seals) and those whose capillary entry pressures are so high that seal breach occurs by fracturing of the cap rock (hydraulic seals) (Watts 1987). Therefore, an evaluation of a rock's seal potential, as defined by Kaldi & Atkinson (1997), incorporates an assessment of seal geometry (seal thickness and lateral extent), seal capacity (the hydrocarbon column a seal can support) and seal integrity (the seal's propensity to develop structural permeability).

Seal integrity forms an integral part of seal potential evaluation, but is unfortunately beyond the scope of this project. A brief discussion of the main factors that influence seal integrity will be given and a basic, qualitative evaluation based on the lithologies observed in core will be provided.

6.2 Seal Capacity

Seal capacity is defined as the maximum hydrocarbon column height a seal can hold back, and is dependent on the capillary properties of the rock (Vavra et al. 1992). In the following, the principles and methodology behind seal capacity evaluation will be presented, and seal capacity results from the various Eumeralla Formation facies will be compared and discussed in terms of lithology and mineralogy.

6.2.1 PRINCIPLES OF CAPILLARY PRESSURE

Capillary pressure is the main resistive force to secondary hydrocarbon migration. Its magnitude is determined by the interfacial tension acting between the hydrocarbons and the formation water, the contact angle between the reservoir fluids and the rock, and the radius of the largest interconnected pore throats (Fig. 6.1) (Schowalter 1979). Interfacial tension can be defined as the work required to enlarge, by unit area, the interface between two immiscible fluids (Schowalter 1979). Buoyancy is the density difference between the hydrocarbon and water phase, and is the main driving force for migration. Capillary pressure can be measured in the laboratory using MICP analysis.

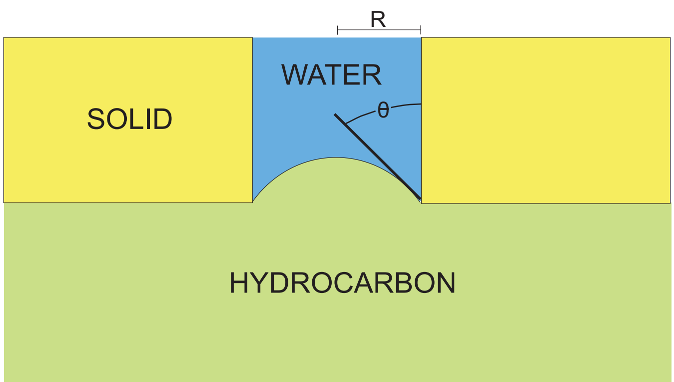


Figure 6.1 Capillary pressure is a function of the contact angle of the hydrocarbon and water against the solid (2), the radius of the largest interconnected pore throats (R), and the interfacial tension acting between the hydrocarbons and the formation water. Modified from Schowalter (1979).

6.2.2 MICP ANALYSIS AND METHODOLOGY

A Micromeritics Autopore-III mercury porosimeter was used to investigate capillary threshold pressures and pore-throat size distributions for the sampled lithologies. The instrument is able to inject mercury at user-defined pressure increments, thereby deriving both a cumulative and an incremental pore volume curve. In the laboratory air-mercury system, mercury is the non-wetting phase and represents hydrocarbon, which is the non-wetting phase in the subsurface. Air is the wetting phase and represents water, which is the wetting-phase in the subsurface. The entry pressure (Pe) is the pressure at which mercury starts to penetrate the pores of the rock. The threshold pressure (Pth) is the pressure at which a continuous filament of non-wetting phase (mercury) extends through the pore network of the sample, and represents capillary seal breach (Katz & Thompson 1987). This occurs at a sample specific pressure dependent on pore-throat size, and is associated with a rapid increase in mercury intrusion. Graphically, the threshold pressure is determined from the lower inflection point on the cumulative mercury injection curve and a large gradient increase on the incremental volume injection curve (Fig. 6.2). Initial increases in pressure are due to mercury entering surface voids and fractures, a process called conformance. Cuttings and sidewall cores are typically associated with an indistinct and gradual mercury intrusion curve, but with the additional incremental injection curve these threshold pressures can be picked with greater certainty.

Core samples were coated with epoxy resin (Araldite) on five sides to ensure that the mercury entered the samples only perpendicular to bedding. Some of the samples were not coated because a bedding orientation could not be determined with certainty. The samples were then oven-dried overnight. Data generated from different drying techniques indicate that threshold pressure is not significantly affected by drying methodology (Dewhurst et al. 2002).

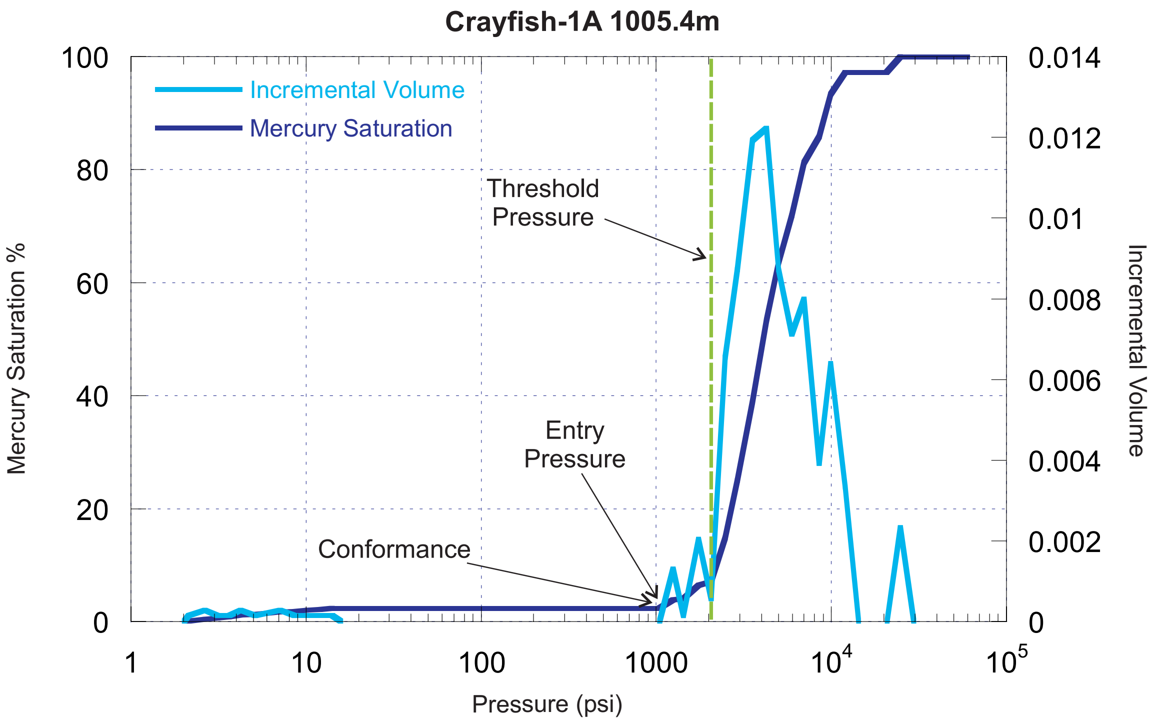


Figure 6.2 Mercury injection capillary pressure curve and terminology.

6.2.3 CALCULATION OF Hmax

Based on the MICP results, seal capacity (Hmax) was calculated using the following equation from Smith (1966):

$$H_{\max} = \frac{P_S - P_R}{(\rho b - \rho hc)1.42} \qquad (1)$$

Where:
H_{max} - maximum height of hydrocarbon column (m)
P_S - brine/hydrocarbon threshold pressure of the seal (psi)
P_R - brine/hydrocarbon threshold pressure of the reservoir (assumed at 1 psi)
ρb - subsurface brine density (g/cc)
ρhc - subsurface hydrocarbon density (psi/ft)
1.42 - gravity constant (psi/m)

First, the laboratory-derived air-mercury pressures were converted to the brine-hydrocarbon system at subsurface conditions using the following equation from Purcell (1949):

$$Pc_{b/hc} = Pc_{a/m} x \frac{\sigma_{b/hc} \cos\theta_{b/hc}}{\sigma_{a/m} \cos\theta_{a/m}} \qquad (2)$$

Where:
$Pc_{b/hc}$ - capillary pressure in the brine/hydrocarbon system (psi)
$Pc_{a/m}$ - capillary pressure in the air/mercury system (psi)
$\sigma_{b/hc}$ - interfacial tension for the brine/hydrocarbon system (dynes/cm)
$\sigma_{a/m}$ - interfacial tension for the air/mercury system (dynes/cm)
$\theta_{b/hc}$ - contact angle of the reservoir brine/hydrocarbon/solid system
$\theta_{a/m}$ - contact angle of the laboratory air/mercury/solid system

An interfacial tension of 480 dynes/cm and a contact angle of 140° are standard values for air/mercury systems (Vavra et al. 1992). Interfacial tension values for the brine/hydrocarbon system were determined using a nomograph of Clinch (1996), derived by combining all data on gas/water surface tension published in Society of Petroleum Engineers (SPE) papers (Fig. 6.3). A nomograph by Schowalter (1979) is more commonly used for determining interfacial tension values (Fig. 6.4), however, Clinch (1996) was used because this nomograph provides a better constraint under high-pressure conditions (Fig. 6.3). The two nomographs give very similar values, suggesting that the use of one over the other has an almost negligible effect on calculated hydrocarbon column heights (Table 6.1). Sensitivities to possible variations were added to the calculations for both interfacial tension and contact angle. A 10dynes/cm range

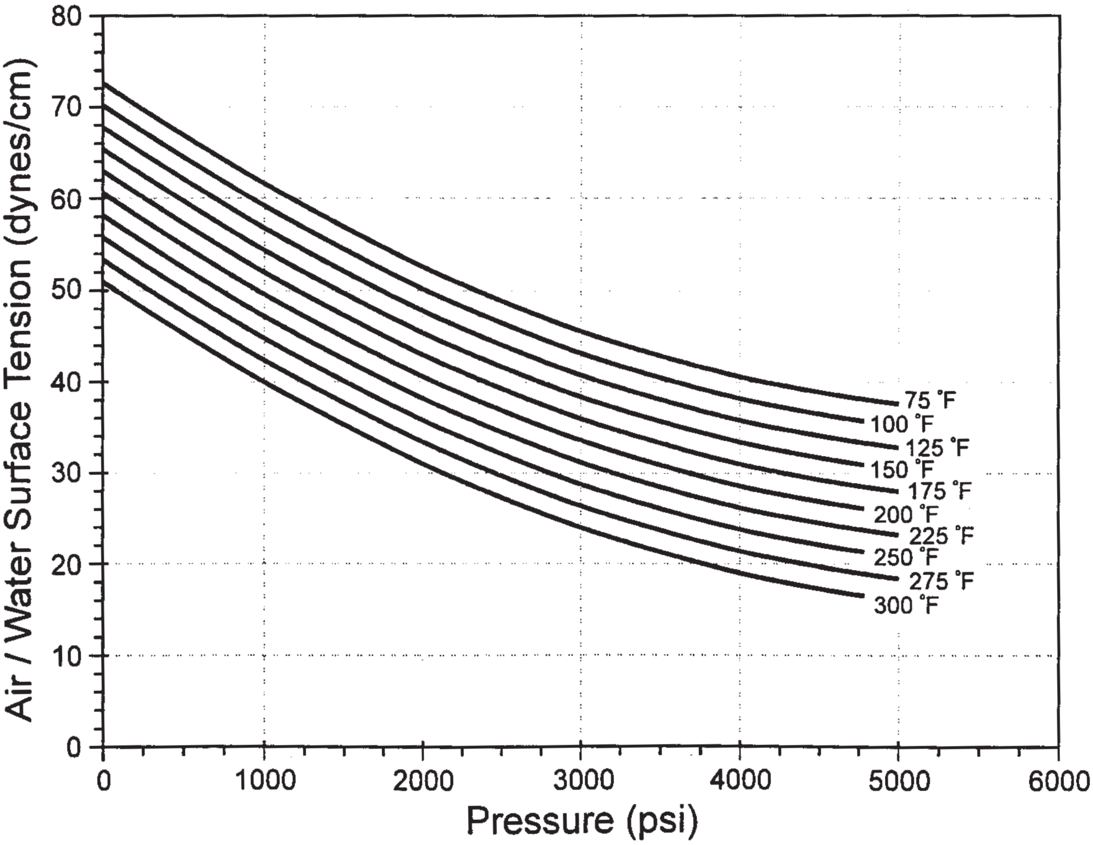


Figure 6.3 Gas water surface tension nomograph (Clinch 1996).

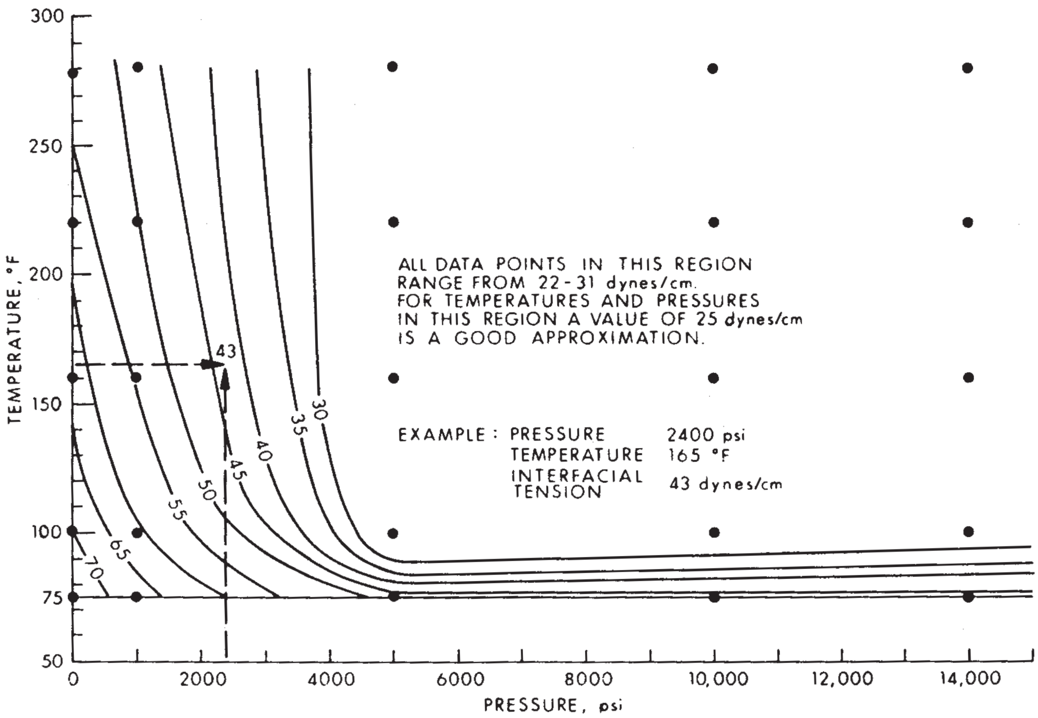


Figure 6.4 Nomograph to estimate methane-water interfacial tension at different temperatures and pressures (black circles are experimental data points and extrapolated curves from Hough et al. 1951) (Schowalter 1979).

Well	Depth (m)	Sample	Pressure (psi/m)	Pressure (psi)	Temp (F)	Salinity	Density		Interfacial Tension	
							Brine	*Gas*	*Clinch*	*Schowalter*
Offshore:										
Crayfish-1A	1005.4	Core	1.4518	1459.64	115.8	35000ppm NaCl	1.03	0.1758	54	54
Crayfish-1A	1175.7	Core	1.4518	1706.88	135.4	35000ppm NaCl	1.02	0.1758	50	50
Crayfish-1A	1528.75	Core	1.4518	2219.4	176	35000ppm NaCl	1.01	0.1758	42	42
Sophia Jane-1	1515-1520	Cuttings	1.4518	2206.74	167.4	35000ppm NaCl	1.00	0.1758	43	43
Troas-1	1030-1050	Cuttings	1.427	1470	127.4	23300 ppm tds	0.99	0.1758	53	53
Troas-1	2020-2030	Cuttings	1.427	2896.8	206.6	23300 ppm tds	0.97	0.1758	34	36
Trumpet-1	877.8-896.1	Cuttings	1.4518	1300.95	116.6	29000ppm tds	1.00	0.1758	55	55
Trumpet-1	1268-1280.2	Cuttings	1.4518	1858.59	145.4	29000ppm tds	1.00	0.1758	48	48
Onshore:										
Diamond Swamp-1	1344.2-1350.3	Cuttings	1.623	2191.5	125.1	25668.5 ppm tds	1.00	0.1714	46	46
Geltwood Beach-1	3016.3	Core	1.623	4895.5	191	25668.5 ppm tds	0.99	0.1714	28	~ 25
Geltwood Beach-1	3725.1	Core	1.623	6045.8	223	25668.5 ppm tds	0.99	0.1714	24	~ 25
Kalangadoo-1	1194.2	Core	1.686	2013	133	24467ppm tds	1.00	0.1714	47	47
Kalangadoo-1	1363.7	Core	1.686	2298.8	142	24467ppm tds	1.00	0.1714	45	45
Kalangadoo-1	1869.3	Core	1.686	3151.6	158	24467ppm tds	1.00	0.1714	36	37
Lake Eliza-1	887-893	Cuttings	1.623	1505.6	122	26870 ppm tds	1.01	0.1714	53	54
Lake Eliza-1	1060.7-1066.8	Cuttings	1.623	1799.69	123.8	26870 ppm tds	1.01	0.1714	50	51
Mocamboro-11	617.72	Core 11F	1.621	1001.32	170.6	33846 ppm tds	1.01	0.1714	59	59
Mocamboro-11	706	Core 13B	1.62	1144.43	172.4	33846 ppm tds	1.01	0.1714	57	57
Mocamboro-11	744.69	Core 14D	1.621	1207.14	172.4	33846 ppm tds	1.01	0.1714	56	56
Mocamboro-11	871.35	Core 21C	1.621	1412.46	185	33846 ppm tds	1.01	0.1714	54	54
Mocamboro-11	907.2	Core 22	1.621	1470.57	185	33846 ppm tds	1.01	0.1714	53	54
Mocamboro-11	943.2	Core 23	1.621	1528.93	109.6	33846 ppm tds	1.01	0.1714	52	53
Reedy Creek-1	1668	SWC 45	1.623	2707.2	114.3	25668.5 ppm tds	1.00	0.1714	40	40
Reedy Creek-1	1678.5	SWC 43	1.623	2724.2	116.3	25668.5 ppm tds	1.00	0.1714	40	39
Reedy Creek-1	1701	SWC 42	1.623	2760.7	123.1	25668.5 ppm tds	1.00	0.1714	39	38
St Clair-1	1924m	SWC 60	1.623	3122.65	124.9	25668.5 ppm tds	0.99	0.1714	35	36
St Clair-1	1950m	SWC 59	1.623	3164.85	126.8	25668.5 ppm tds	0.99	0.1714	35	36

Table 6.1 Values derived from well completion reports were used to calculate seal capacities within the sampled wells. Interfacial tension values derived from the nomographs of Clinch (1996) and Schowalter (1979) are very similar.

was used for interfacial tension. The contact angle associated with gas is commonly assumed to be zero degrees (Vavra et al. 1992). However, a range from zero to ten degrees was used as gas contact angle may be as high as 10 degrees.

Pressure data were not available for all of the sampled wells, and average values from drill stem tests of a few wells had to be used (Table 6.2). Brine density at subsurface conditions was determined from a nomograph of Schowalter (1979) based on temperature, pressure and salinity. An average salinity value was derived from Lake Eliza-1, Lake Eliza-2 and Kalangadoo-1 data and applied for onshore wells where no reliable salinity data were available. A gas density value from Troas-1 was used for all of the offshore wells, as these are located relatively close to each other (Fig. 6.1). For the onshore wells, an average of Troas-1 and Haselgrove-1 gas density values was used (Table 6.1). A range of 0.17-0.18psi/ft of gas density was used for calculations and a 1.0-1.5g/cc range of brine density. Only potential gas column heights were calculated as most of the Otway Basin discoveries have involved gas, and very limited data are available for determining oil densities outside of the Penola Trough.

Wellname	Pressure data from DSTs (psi/m)	Average Values Used
Crankshaft-1	1.584	Onshore South Australia: 1.623
Kalangadoo-1	1.686	
Ladbroke Grove-1	1.558	
Laira-1	1.625	
Lake Eliza-1	1.687	
Lake Eliza-2	1.595	
Crayfish-A1	1.452	Offshore South Australia: 1.439
Troas-1	1.427	
Digby-1	1.621	Onshore Victoria: 1.621

Table 6.2 Pressure gradients derived from well completion reports and used for calculating seal capacity.

6.2.4 SEAL CAPACITY RESULTS

Threshold pressures for the sampled lithologies in eleven Otway wells range from 60 psi to over 9000 psi (Table 6.3). The deeper lacustrine Unit VI sediments have capillary threshold pressures of 5979psi in a Mocamboro-11 core sample and 1459psi in a St Clair-1 sidewall core sample (Table 6.3). A siltstone that represents the coarsest Unit VI interval observed in core has a threshold pressure of over 4000psi (Table 6.3). Within the shallow lacustrine to floodplain sediments of Unit V, threshold pressures vary from 1407-9000psi for core samples, 340-625psi for cuttings samples, and 68-85psi for sidewall core samples (Table 6.3). Core samples from Geltwood Beach-1 have high threshold pressures both within Unit V and Unit IV sediments (Table 6.3). Threshold pressures within Unit IV cuttings samples varies between 239-339psi, whereas the values in the overlying shallow lacustrine Unit III ranges from 728psi to 2049psi (Table 6.3). Within Unit II, capillary threshold pressures for core samples range from 1425-5002psi (Appendix D, Table 6.3). No samples were analysed from Eumeralla Unit I.

The above threshold pressures (Table 6.3) equate to gas column heights ranging from 4 metres to 812 metres (Fig. 6.5). The results show there are intervals present within all of Eumeralla Formation Units II through to VI that are capable of holding a considerable column of gas (Fig. 6.5). The very broad ranges of values (Fig. 6.5) are due to sensitivities for interfacial tension, contact angle and subsurface densities. Variations in contact angle (0-10°) have a very limited effect on calculated gas column heights relative to the effect of variations in interfacial tension (+/- 5 dynes/cm) (Fig. 6.6).

INTERVAL	CRAYFISH-1A	DIAMOND SWAMP-1	GELTWOOD BEACH-1	KALANGADOO-1	LAKE ELIZA-1	MOCAMBORO-11	REEDY CREEK-1	SOPHIA JANE-1	ST CLAIR-1	TROAS-1	TRUMPET-1
Unit II - Floodplain	2062			3214*						60	
Unit III - Shallow lacustrine	2049										728
Unit IV - Floodplain			>9000		239					339	
Unit V - Floodplain		341			340	3917*		625			
Unit V - Shallow lacustrine	6023		>9000*	8485		1407*	68		85		
Unit VI - Deep lacustrine (silty)						4248*					
Unit VI - Deep lacustrine						5979*			1459		
Sample Type	C	CT	C	C	CT	C	SWC	CT	SWC	CT	CT

Table 6.3 Threshold pressures for various lithologies occurring within Eumeralla Formation Units II to VI. Values in red represent average values. Samples that were glued with epoxy resin are marked (*).

6.2.5 DISCUSSION OF SEAL CAPACITY RESULTS

The samples derived from core give considerably larger column heights than both sidewall cores and cuttings samples, with values commonly approximating 200-800 meters (Fig. 6.5). These values reflect a similar variation seen in threshold pressures for the different sample types (Table 6.3). The sidewall core samples were in a relatively poor condition as the bulk

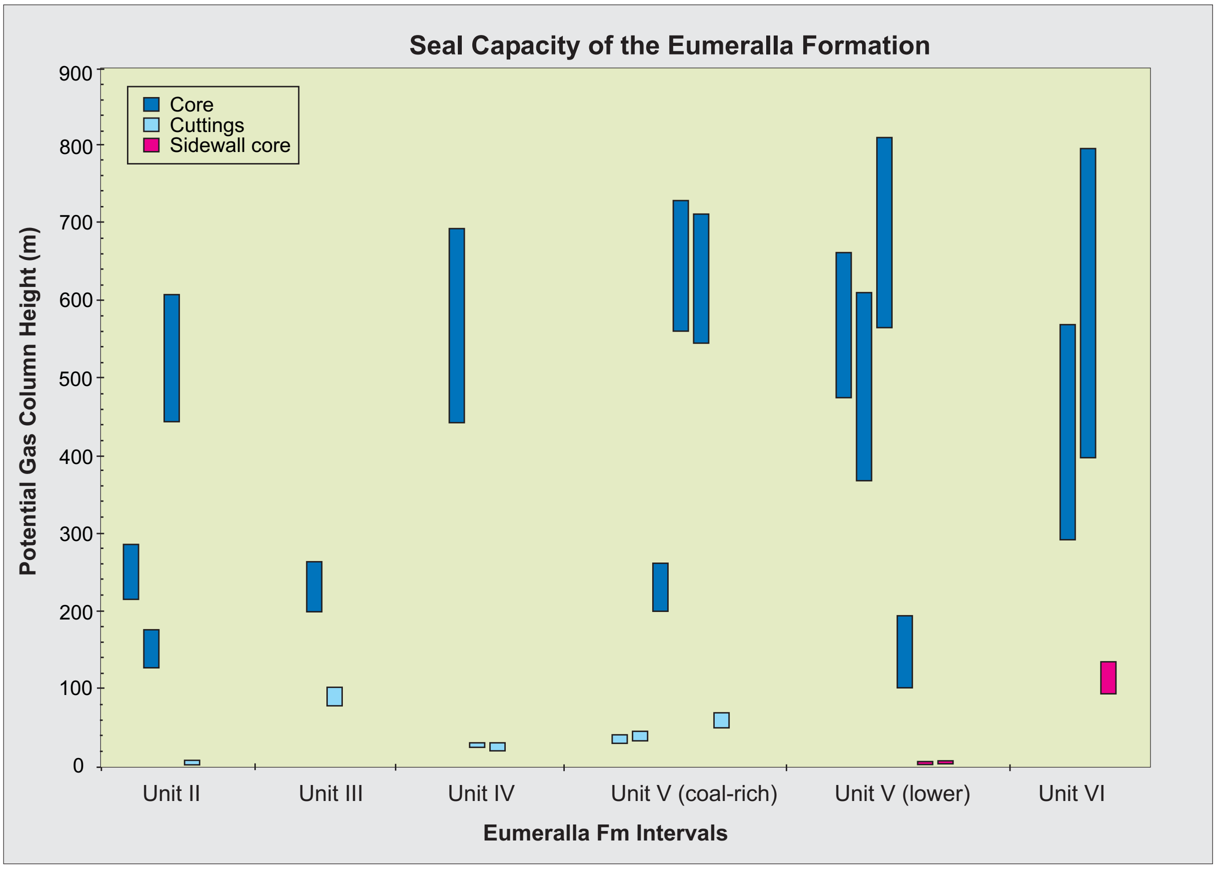


Figure 6.5 Potential gas column heights held by various Eumeralla Formation facies in the sampled Otway wells. The bars are due to sensitivities added to calculations. Samples derived from core give considerably higher seal capacities than sidewall cores and cuttings samples.

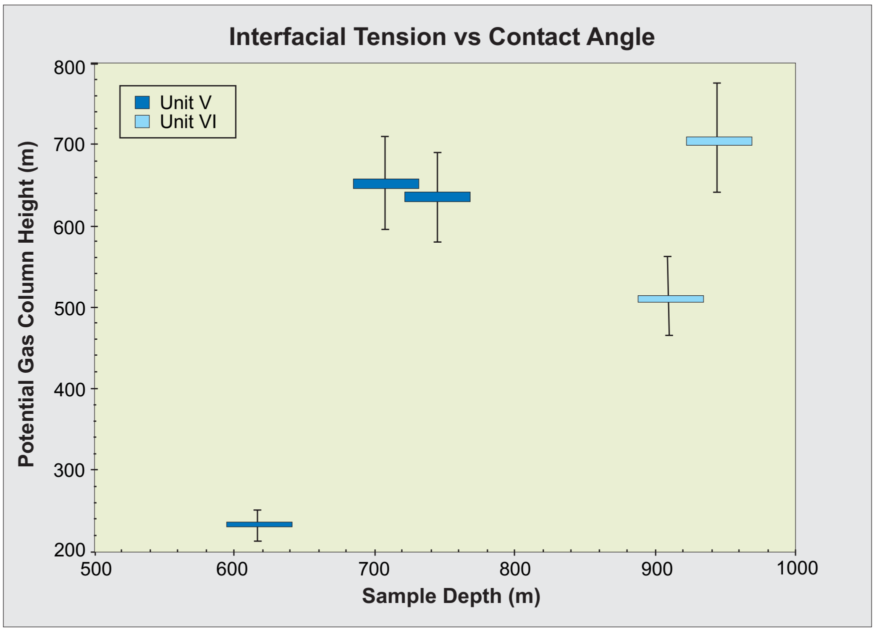


Figure 6.6 Both Unit V and Unit VI sediments have high seal capacities. Error-bars represent a range of values for interfacial tension, while blue boxes represent a range of values for contact angle. Variations in interfacial tension have a greater effect on calculated column heights than variations in contact angle. All samples are taken from Mocamboro-11 core.

part of the samples had already been removed. Percussion sidewall cores are also prone to fracturing when recovered, and resulted in very low threshold pressures for the Reedy Creek-1 and St Clair-1 samples (Table 6.3).

The large differences in threshold pressures between the core and cuttings samples are most likely associated with the interbedded nature of the Eumeralla Formation. Cuttings samples are collected over an interval of 3-5 meters and will therefore include sediments from coarse-grained interbeds, as well as siltstones and shales. During core sampling, however, a small sample is collected to represent a large stratigraphic interval. Sediments from thin, coarser-grained interbeds may not be accounted for, resulting in a dominantly finer-grained sample that provides high capillary threshold pressures and large potential gas column heights.

For the purpose of comparing seal capacities between a large number of samples from different wells, threshold pressure can be a useful indicator of seal capacity rather than calculated hydrocarbon column heights (Kovack et al. 2003). The use of calculated column heights makes comparison between wells problematic, as it is related to poorly constrained and variable input parameters that are dependent on pressure and temperature. Threshold pressure depends on a sample’s pore geometry, interconnectivity and pore-throat size, all of which are directly related to lithology (Kovack et al. 2003).

Both Unit VI and Unit V sediments have high threshold pressures. The shallow lacustrine to floodplain sediments of Unit V give slightly more variable threshold pressures, likely to reflect the range of lithologies occurring within this sequence. The large difference in threshold pressures within the sidewall core samples in St Clair-1 (1459 psi in Unit VI versus 85 psi in Unit V) suggests that the deep lacustrine sediments of Unit VI provide better sealing lithology than the shallow lacustrine sediments of Unit V.

In core, the lower Unit V consists of multiple fining-upward lacustrine sequences providing lithologies ranging from shales to medium sandstones (Fig. 4.13). The capillary properties of these sediments are variable, and the best sealing lithologies are thin and interbedded with sandstones and siltstones that have low threshold pressures (i.e. are poor seals). Within Unit VI, a massive claystone interval, close to a meter thick, is present in Mocamboro-11 core and the siltstone interbeds are thin and fine-grained.

Thin sections from the lower Unit V show extensive secondary porosity development due to dissolution of feldspar (Fig. 4.14). Unit VI is finer-grained and matrix-dominated, with quartz-rich, siltstone interbeds showing only minor secondary porosity (Fig. 4.10). The visible porosity only occurs as isolated pores, resulting in a very low permeability. Carbonaceous material orientated parallel to bedding is likely to cause a more tortuous path for fluid flow, thereby further increasing the sealing properties of Unit VI sediments.

The fine-grained sediments of Unit IV have no visible porosity and have high threshold pressures. Their deposition within a floodplain environment implies that the sediments are likely to be variable, similar to the Unit V sediments. Seal capacities may vary greatly between the various sub-environments present within the floodplain. Units III and II generally have lower threshold pressures than the underlying Eumeralla Formation facies. Both sequences are very sand rich, indicated by an overall coarsening-upward trend on logs (Fig. 4.7). The sediments within Unit III are poorly consolidated with a high porosity and permeability, and are unlikely to provide good sealing lithology (Fig. 4.22).

6.2.6 MINERALOGY AND SEAL CAPACITY

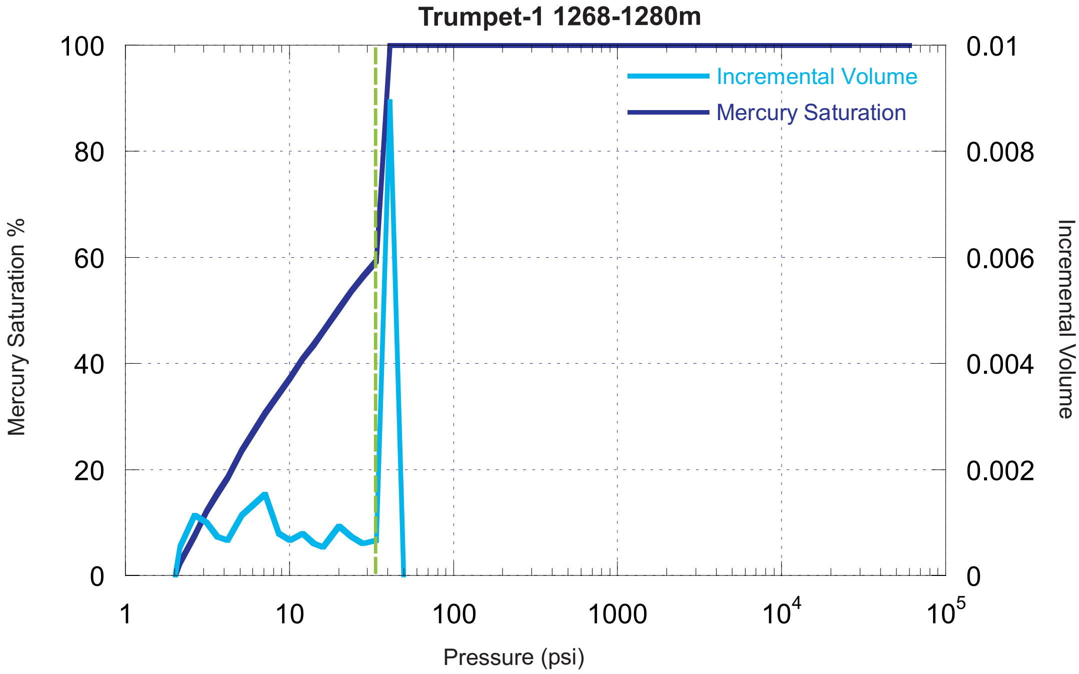
Samples from Geltwood Beach-1 have unusually low MICP calculated porosities and high threshold pressures (Table 6.3, Appendix D). The glued and the unglued samples have a similar threshold pressure (>9000psi), suggesting that the values are not related to sample preparation. Only a very minor amount of mercury was intruded at even high pressures, and this amount is not more than what would be required to fill surface rugosity of the core samples. The samples were taken from over 3,000 m depth, suggesting pore volume loss may be more affected by mineral reactions than mechanical compaction (Matthews et al. 2000). Kaolinite cement and illite are well developed within the lower sections of this well (Montague 1989). Montague (1989) investigated non-calcareous sandstones within Unit V, and noted that matrix has occluded all primary pore spaces and prevented the development of any secondary porosity. Samples from all other wells are from considerably shallower depths. Mechanical compaction reduces pore throat size (Dewhurst et al. 1998) and is likely to be a main factor influencing seal capacity at shallower intervals.

The transition from smectite to illite is a function of depth as the reaction accelerates at temperatures between 60˚C and 120˚C (Bjørkum & Nadeau 1998; Matthews et al. 2000). Both Unit V and Unit VI have a high illite and smectite content (Fig. 4.12). Unit V contains more illite, and especially has a higher percentage of illite within the illite-smectite interbeds of the clay fraction (<2μm) (Fig. 4.12). The small clay fraction can easily change orientation and thereby affect pore throat size distribution and hence, seal capacity (Dewhurst et al. 2002). However, further research is required to evaluate how smectite-rich shales and smectite-illite transition may affect seal capacity. Duddy (1997) suggested that the extreme diagenetic alteration seen within the Eumeralla Formation may have had a profound effect on restricting migration pathways, particularly the movement of oil through extremely low permeability sandstones.

A cuttings sample from Unit V in Trumpet-1 did not provide a true measurement of capillary threshold pressure, as the mercury got into the inter-particle space (i.e. between cuttings) but did not enter the matrix pore system (Fig. 6.7). The sample is very calcareous and also contains abundant organic matter (Fig. 6.8). The extremely low MICP calculated porosity is not likely to result from the calcite as very calcareous samples from other wells have normal threshold pressure curves (Appendix D). Work by Almon et al. (2002) on deepwater shales in outcrop and in the subsurface also suggests that seal capacity varies with textural and compositional factors and that silty shales have a higher seal capacity than silty calcareous shales. The low porosity within the Trumpet-1 sample is more likely to be associated with its very high organic content (Fig. 6.8). Nevertheless, extensive calcite cement and calcite concretions are capable of strongly modifying the permeability of sandstone reservoirs and can affect fluid flow during production (Dutton et al. 2002).

6.3 Seal Geometry

Seal geometry refers to seal thickness and also the lateral extent of the seal (Kaldi & Atkinson 1997). Seal thickness does not linearly influence the size of the hydrocarbon column that can be held by a seal, however, a thick seal provides many layers of sealing beds and a larger probability that an unbreached sealing surface will be distributed over an entire prospect (Downey 1984). Facies analysis involving an evaluation of log, seismic and core data provides the basis for recognising how sealing facies are developed vertically and laterally. A sequence stratigraphic approach to seal analysis may increase the understanding of seal geometry and interconnectivity, and thereby help predict seal potential.



Interval: Eumeralla Fm Unit V
Sample Type: Cuttings
Lithology: Black carbonaceous siltstone
Clay Mineralogy: Quartz, calcite, feldspar, kaolinite, illite, chlorite, smectite
MICP Calculated Porosity: 6.1518%
Threshold pressure: 33psi – – – (Not true threshold pressure)

Figure 6.7 Cuttings from the black carbonaceous siltstone in Trumpet-1 have a very low MICP-calculated porosity, resulting in almost no mercury intrusion even at high pressures. It is unlikely that this measurement represents the sample's true threshold pressure.

Figure 6.8 Cuttings from a Unit V black carbonaceous siltstone in Trumpet-1 (1268-1280m). Calcite is present as white to light gray fragments.

Both the overall distribution of the various Eumeralla Formation facies and their likely geometry based on sequence stratigraphic principles were discussed in previous sections (Chapter 4.11.2 and Chapter 5.3). To summarise, although Unit II represents the thickest Eumeralla interval throughout most of the western Otway Basin, the sediments have poor seal geometry. The interval is very sand-dominated as it consists of amalgamated fluvial channel deposits interbedded with finer-grained floodplain deposits. The underlying Unit III sediments are less sand-dominated, and are likely to be laterally more extensive due to their deposition in a transgressive, lacustrine environment. The floodplain sediments of Unit IV and V are variable and may not be very laterally continuous, however, the sediments represent a relatively thick section of predominantly fine-grained sediments. Unit VI provides excellent sealing lithology that has a maximum thickness of less than hundred meters in the wells investigated. The overall risk associated with the seal geometry of Unit VI is considered higher than Unit V because of its more local development.

6.4 Discussion of Seal Integrity

Seal integrity can be considered as the seal rock propensity to develop structural permeability (Sibson 1996). The *in situ* stress conditions, the mechanical properties of the sealing rock, and the buoyancy pressure of the hydrocarbon column determine the probability of top seal brittle failure (Hillis et al. 2004). Several mechanisms can provide enhanced permeability and leakage through the seal, such as tectonically induced, dilatant faulting and fracturing in brittle rocks, tectonic fault displacement in excess of the seal thickness, tensile fracturing under extreme fluid pressure conditions; and leakage via a network of juxtaposed thin leaky beds across sub-seismic faults within the seal (Ingram & Urai 1999). Seal integrity can be measured in a laboratory or evaluated qualitatively by core examination, borehole imaging and petrographic studies (Jones et al. 2000).

6.4.1 IN SITU STRESS AND STRUCTURAL CURVATURE

The *in situ* stress at any given location is determined by the orientation and relative and absolute magnitudes of the three principal *in situ* stresses; maximum horizontal stress, minimum horizontal stress and vertical stress (Ameen 2003). There is often a strong correlation between the preferred flow directionality and maximum *in situ* stress direction. Fractures that are parallel to maximum *in situ* stress tend to remain open, whereas fractures that are perpendicular to the maximum *in situ* stress tend to close (Ozkaya 2002). *In situ* stress direction can be measured from borehole breakouts, whereas the magnitude of vertical stress can be estimated from density logs (Ozkaya 2002). The ratio of minimum to maximum horizontal stress can be determined by well bore breakouts and leak-off tests (Ozkaya 2002). Leak-off tests measure the total pressure required to fracture the rock in the region near the well bore (Converse et al. 2000).

There is commonly a relationship between areas of high surface curvature and fracture density (Murray 1968, Stewart & Podolski 1998). Structural curvature can therefore be used to predict fracture density distribution over a reservoir (Ozkaya 2002). Ozkaya (2002) states that both fracture density and fracture orientation must be known to predict the flow potential of fractures. This is because fracture flow depends on aperture which in turn depends on fracture orientation with respect to maximum horizontal *in situ* stress direction and maximum to minimum horizontal stress ratio (Ozkaya 2002). Fracture distribution through the seal can be observed on image logs (Mildren et al. 2002). Other factors that influence fracture flow and fracture potential are rock type, bed thickness, proximity to faults and mineralization (Ozkaya 2002).

6.4.2 CAP ROCK STRENGTH

The strength of a sealing rock is determined not only by regional stresses but also by the rock's mechanical properties such as ductility and compressibility. Ductility is a rock property that varies with pressure and temperature (burial depth) as well as with lithology (Downey 1984). Seal rheology determines the failure mode, i.e. whether the rocks are ductile and remain sealing after deformation or whether they deform in a brittle manner to create permeable leak paths (Ingram & Urai 1999). Rocks with high seal integrity, such as salts and anhydrites are better seals than brittle rocks like coals, dolomites and quartzites (Jones et al. 2000). Generally, as the carbonate content or the siliciclastic grainsize of the seal lithology increases, the propensity to develop structural permeability increases (Kivior & Kaldi 2002). Seals that contain a large amount of leaky strata, such as coarse silts or sandstone interbeds, are much more prone to leakage in the presence of faults than massive mudrocks (Ingram & Urai 1999).

Mudrocks are considered very effective top seals because they have very low permeabilities, high capillary entry pressures and typically are laterally continuous across a basin (Ingram & Urai 1999). However, mudrock rheology will vary within a basin, from areas in which rocks are strong and brittle (in uplifted over-consolidated blocks, or locally cemented pockets) to areas in which the rocks are soft and ductile (uncemented, undercompacted, high swelling clay mudrocks) (Ingram & Urai 1999). In tight or very pure mudrocks, it is unlikely that hydrocarbon leakage will occur by Darcy flow through matrix porosity (Hall et al. 1986). Leakage through fracture networks provide the main risk and leak mechanism for such mudrocks (Ingram & Urai 1999).

In situations where the cap rock is stronger than fault rocks (eg. cemented cataclasites as described by Dewhurst & Jones, 2002), cap rock failure represents the main risk and fault orientation with respect to the *in situ* stress does not need to be considered (Hillis & Nelson 2005). Cap rock strength can be determined from wireline logs or from laboratory rock strength tests (Milden et al. 2002). By combining these estimates with knowledge of the *in situ* stress tensor, the critical pressure change required to induce brittle failure can be determined (Mildren et al. 2002).

6.4.3 EFFECT OF SMECTITE-ILLITE TRANSFORMATION ON SEAL INTEGRITY

Geomechanically, smectite is considered the weakest of minerals, while kaolinite tends to have the highest friction coefficients among the clay minerals (Dewhurst et al. 1998). In a rock where the dominant framework mineral is smectite or mixed layer smectite-illite, alteration of the mineral framework through diagenesis is likely to affect rock strength through changes in friction coefficient and cohesive strength (Dewhurst et al. 1998). Within the Muderong Shale, the regional seal in the Carnarvon Basin on the Australian North West Shelf, seismic leakage indicators were found to be located on small faults associated with dominantly smectite-illite and quartz top seal intervals (Dewhurst et al. 1998). The transformation of smectite into illite releases water into the pores of a sediment, thereby increasing the pore pressure (Gaarenstroom et al. 1993). Foster & Custard (1980) concluded that smectite-illite transformations increase the pore pressure due to a decrease in permeability.

6.4.4 GEOMECHANICAL RISKING STRATIGIES

Early geomechanical work on fracture-related seal breach focused mainly on tensile failure of the cap rocks (Hillis & Nelson 2005). Gaarenstroom et al (1993) introduced the concept of retention capacity as the difference between the minimum horizontal stress and pore pressure. A positive retention capacity reflects that additional pore pressure (or hydrocarbon column height) can be developed prior to tensile fracturing occurring (Gaarenstroom et al. 1993).

However, retention capacity only considers the risk of tensile (and not shear) failure of the cap rock and does not incorporate (tensile) rock strength (Hillis & Nelson 2005). Fractures that are orientated such that they are subjected to both shear and tensile stresses can be critical conduits for fluid flow (Ameen 2003). A comprehensive analysis of the risk of fracture-related seal breach requires a consideration of the likelihood of tensile or shear failure of intact cap rocks, as well as the risk of post-charge reactivation, in tension or shear, of fault seals (Hillis & Nelson 2005). Jones et al. (2000) can be referred to for an outline of fault seal evaluation strategies, whereas Hillis & Nelson (2005) provide a detailed review of exiting geomechanical risking methodologies.

6.4.5 MECHANICAL PROPERTIES OF EUMERALLA INTERVALS

Although no seal integrity analysis was conducted as part of this project, some predictions can be made about the relative seal integrity of Eumeralla Formation intervals based purely on lithology and core examination. Coals are typically very brittle. Their abundant occurrence within the floodplain sediments of Unit V suggests this interval is associated with a high risk of brittle failure and low seal integrity. High angle fault planes with slickensides occur within the sediments in core (Appendix B). The very minor coals described in cuttings from Unit VI are not distinguishable on seismic or wireline logs. These coals occur more sporadically and are likely to be thin and not laterally extensive, thereby giving Unit VI higher seal integrity. The massive claystone developed within Unit VI is also likely to provide a more reliable seal than the interbedded sandstones, siltstones and shales of the overlying Unit V. The highly interbedded strata are more prone to leakage where faults and fractures are developed.

The high smectite-illite content of the lower Eumeralla Formation (Units V and VI) is likely to be a main factor influencing the sediments' cap rock strength. Smectite is considered a weak mineral (Dewhurst et al. 1998), suggesting the lower Eumeralla sediments are likely to have a more ductile behaviour than the upper Eumeralla Formation intervals. However, the added pore pressure from smectite-illite transitions may increase the risk of leakage, as observed by Dewhurst et al. (1998) within the smectite-rich Muderong Shale.

Eumeralla Units IV and II are expected to have moderate seal integrity, as only minor coals are present within these intervals. The risk of brittle failure or juxtaposition of leaky strata is considered high within the sand-dominated Unit II. The very porous and poorly consolidated shallow lacustrine sediments of Unit III are likely to have low seal integrity (Fig. 4.22). These sediments develop fractures along the contact zone between the fine-grained mud rip up clasts and the surrounding coarse framework grains, where porosity is highest (Fig. 4.22). No predictions can be made regarding the seal integrity of the estuarine sediments of Unit I, as the interval was not observed in core.

Overall, the Early Cretaceous shales of the Eumeralla Formation are more brittle than the overlying Late Cretaceous shales and were therefore more prone to rupture during Tertiary reactivation (Boult 2002/03). Jones et al. (2000) conducted a multi-disciplinary assessment of Laira Formation seal integrity in the Penola Trough, and identified fault reactivation as the critical factor associated with seal breach.

6.5 Seal Potential

A basic, relative ranking of the various Eumeralla Formation intervals based on seal geometry, capacity and integrity suggests that Unit VI has got the highest seal potential (Table 6.4). The seal potential values were determined by assigning a value for geometry, capacity and integrity (Excellent: 1, Good: 2, Moderate: 3, Poor: 4) based on the above results and discussions. The purpose of the ranking is to enable a comparison of seal quality between the different Eumeralla intervals, as well as to provide a summary of what sealing factor is likely to represent the main risk within each interval.

Within Unit VI, the risk associated with seal geometry is relatively high because of the interval’s limited distribution (Table 6.4). The sediments have excellent sealing lithology and may provide sufficient sealing at prospect level, but not enough well data is available at present to determine its geometry with certainty. The upper Eumeralla Formation Units II and III have relatively low seal potential as the sediments are more sand-dominated than the lower Eumeralla Formation. No sufficiently thick sealing intervals are likely to be present to overcome the risk of cross fault communication caused by sandstones being fault juxtaposed against sandstones. The floodplain sediments of Unit IV and Unit V are fine-grained, but are likely to be associated with a moderate to high risk of brittle failure due to coal development. The sediments are lithologically variable with relatively high porosities and permeabilities occurring within sandstone and siltstone interbeds.

When combining all of Eumeralla Formation Units II-VI, seal integrity appears to be a higher risk factor in the basin than seal geometry and seal capacity (Table 6.4). This may be due to the large uncertainty associated with the ranking of seal integrity, as no geomechanical assessment was conducted as part of this study. However, the apparent low risk associated with seal capacity and seal geometry of the Eumeralla Formation overall (Table 6.4), highlights the importance of geomechanical risking of Eumeralla seals for future exploration.

Interval	Geometry	Capacity	Integrity	Potential
Unit I	-	-	-	-
Unit II	Poor	Moderate	Moderate	3.3
Unit III	Good	Moderate	Poor	3
Unit IV	Good	Good	Moderate	2.3
Unit V	Good	Good	Poor	2.6
Unit VI	Moderate	Excellent	Good	2
Eum Fm overall	**2.6**	**2.2**	**3.2**	

Table 6.4 A summary and relative ranking of Eumeralla Formation Units I-VI according to their seal geometry, seal capacity and seal integrity. Relative seal potential values have been calculated where the input values were the following; Excellent: 1, Good: 2, Moderate: 3, Poor: 4. Unit VI has the best and Unit II the lowest seal potential. When combining all of the investigated Eumeralla Formation intervals (Units II-VI), seal integrity appears to be a higher risk factor in the basin than seal geometry and seal capacity.

6.6 Implications for exploration

The main risks associated with Eumeralla Formation seals vary between the various Otway Basin troughs and sub regions. Local topography and fault development as well as the distance to the main sources of clastic influx influence sedimentation and sealing properties. Differences in burial depth have resulted in contrasting Eumeralla sealing properties between the northern, largely onshore Otway Basin, and the southern, dominantly offshore parts of the basin.

6.6.1 ONSHORE OTWAY BASIN

Penola Trough

The basal Eumeralla Formation is very silty in the central Penola Trough, and sandstone interbeds are abundant throughout the formation. Sealing lithologies of sufficient thickness and lateral extent to overcome the problems associated with complex faulting are unlikely to be developed here. However, the depositional model proposed for Unit VI suggests that the interval might be developed in the undrilled area in the southern Penola Trough. This area is located to the north of a NW-SE striking segment of the major landward-dipping fault zone separating the Penola Trough and the Kalangadoo High (Fig. 6.9). Ponding and lake development up against the fault block may have resulted in the deposition of a very good seal (Unit VI) at the base of the Eumeralla Formation. Sediments near the base of the Eumeralla Formation in Heathfield-1 (Fig. 6.9) are very fine-grained, but no samples were investigated from this well.

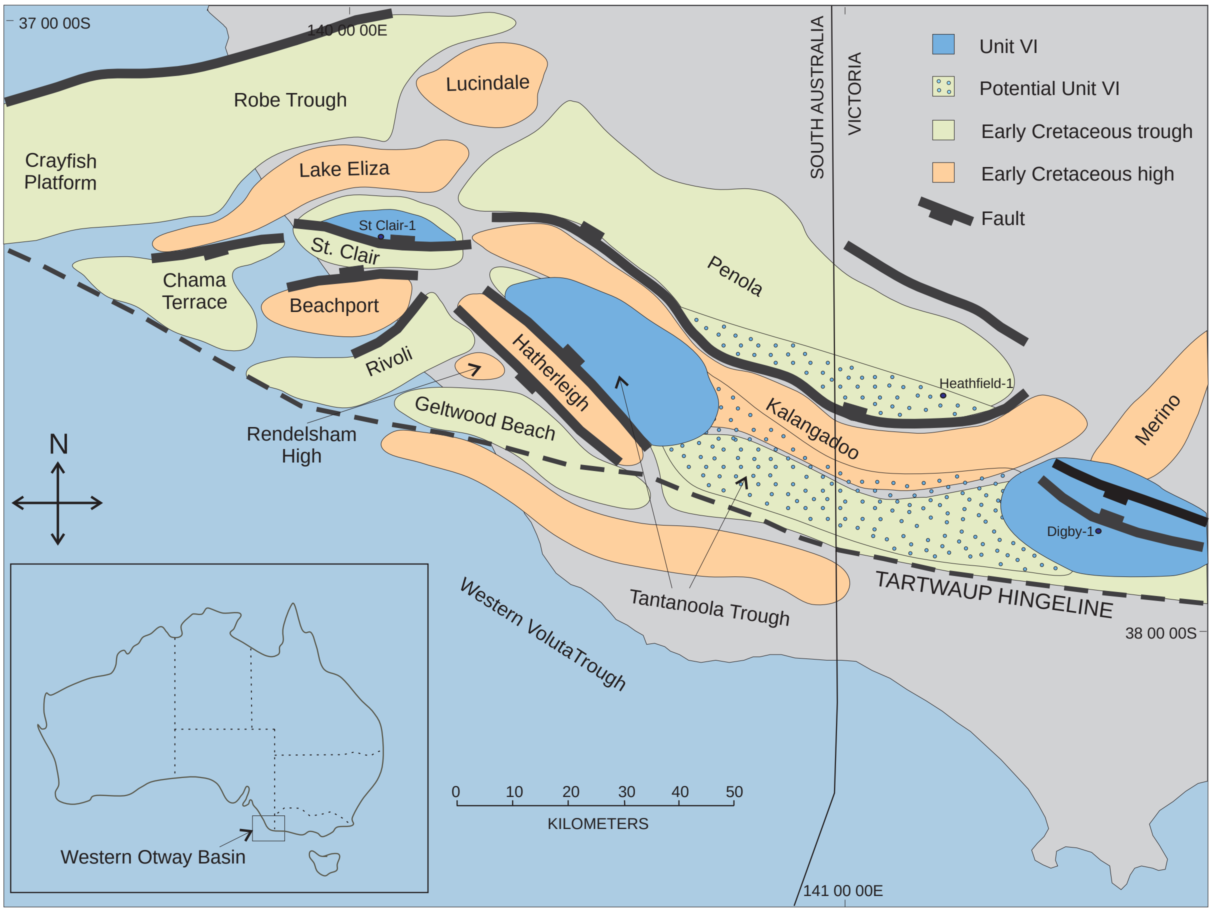


Figure 6.9 The depositional model proposed for Eumeralla Formation Unit VI suggests that the interval, which represents the best seal within the formation, may be developed in the undrilled, southern Penola Trough.

St Clair Trough

The 39-meter thick interval of Unit VI seen in St Clair-1 is likely to represent the maximum thickness of this good seal in the St Clair Trough due to the wells central location within the trough (Fig. 6.9). After drilling of St Clair-1 and Reedy Creek-1, a problem with both top and lateral sealing was recognised. With the St Clair-1 location expected to represent the maximum development of the best sealing lithology, the prospect for the occurrence of a sufficient Eumeralla Formation seal at any other location within the St Clair Trough is thought to be small.

Tantanoola Trough

There is potential for stratigraphic traps to be developed within the western Tantanoola Trough. High threshold pressure lacustrine sediments deposited within a transgressive to early highstand systems tract are likely to provide good seals at the base of the Eumeralla Formation. Interbedded sandstones can provide reservoir facies that are surrounded by these good lacustrine seals. The lower Eumeralla Formation is a very good seal in the eastern Tantanoola Trough, where Unit VI is well developed (Fig. 6.9). The sediments within Digby-1 are dominated by claystones and are finer-grained than equivalent intervals in other wells.

Robe Trough

Unit VI is not developed in Robe Trough, and the lower Eumeralla Formation occurs at a shallower depth here than further to the southeast. The risk of top seal fracturing is considered high in this region due to the occurrence of well-developed coal beds at the base of the Eumeralla Formation in several wells.

6.6.2 OFFSHORE OTWAY BASIN

The southward thickening of the Eumeralla Formation implies that the formation's finer-grained lower intervals are located at great depths in the offshore Otway Basin, including the Chama Terrace, the Rivoli Trough and Geltwood Beach Trough (Figs 4.1, 4.2). The added influence of mechanical compaction and diagenesis has the potential to provide reliable cap seals, regardless of whether Unit VI is developed or not. Only very minor coals are present in cuttings, suggesting the risk associated with seal integrity is much lower than for the Robe Trough and the onshore areas further north. In addition, Boult (2002/03) suggested that shear stresses that cause dilation on reactivated faults are likely to be smaller towards the centre of the Otway Basin over the Geltwood Beach, Rivoli and Tantanoola Troughs.

Chapter 7

Conclusions

7. CONCLUSIONS

A regional study of variations in facies and sealing capacity of the Eumeralla Formation was conducted in order to predict the distribution of intervals with good seal potential for Katnook Sandstone and Windermere Sandstone Member reservoirs. Palynology and sequence stratigraphy were combined with core analysis, log data, seismic data, microscopic analysis and mercury injection capillary pressure analysis. The following conclusions were derived:

Log Correlation:

- The Eumeralla Formation has a high gamma ray log response. SP, sonic and density logs should be used together with the gamma ray log when investigating Eumeralla Formation facies and lithology changes.

- Palynology is a useful tool when correlating Eumeralla formation facies.

Facies:

- The Windermere Sandstone Member is a basal Eumeralla sandstone that overlies the Crayfish Unconformity. The sandstone is lithologically and mineralogically very variable within the Otway Basin. It represents a lowstand systems tract.

- Six Eumeralla Formation facies (Units VI to I) were recognised overlying the Windermere Sandstone Member.

- Eumeralla Formation Unit VI consists of fine-grained, deep lacustrine sediments deposited within a transgressive to early highstand systems tract. The sediments are dominated by illite and smectite and are similar mineralogically to Unit V sediments, except Unit VI is more quartz-rich

- Unit V represents a shallow lacustrine to floodplain-dominated environment. The sediments were deposited in a highstand systems tract and are lithologically very variable. Transitional, shallow lacustrine sediments occurring within the lower Unit V are relatively coarse-grained and have secondary porosity developed from dissolution of feldspar. Abundant coal beds suggest a high risk of brittle failure within Unit V.

- The shallow lacustrine sediments developed within the lower Unit V cannot be differentiated from the fine-grained, deep lacustrine sediments of Unit VI based on seismic data alone.

- The floodplain-dominated sediments of Unit IV represent a late highstand, where coal beds are less developed.

- Unit III consists of shallow lacustrine sediments deposited within a transgressive systems tract. The sediments are very porous. Fractures tend to develop in the contact zone between fine-grained mud rip-up clasts and the surrounding framework grains.

- Calcite cement is common within both Unit IV and Unit III, and is associated with a very distinct log response (fast sonic, high density, high neutron, high resistivity and low gamma).

- Unit II consists of a thick sequence of floodplain sediments deposited within a highstand systems tract. The sediments were deposited at relatively high sedimentation rates. Sandstone packages are well developed within this interval, which coarsens upward.

- Unit I was deposited in an estuarine environment within a transgressive systems tract.

- Illite is the dominant cement throughout the Eumeralla Formation. Smectite is abundant within the lower Eumeralla facies. Authigenic chlorite is present within several intervals throughout the formation, while calcite typically occurs within sandstones and siltstones of Units IV, III and II.

Facies Distribution:

- Eumeralla Formation Units I-V are regional facies present throughout the Otway Basin, whereas the deep lacustrine sediments of Unit VI are more locally developed.

- Unit VI is not necessarily associated with a presence or absence of the algae *Microfasta evansii*.

- Deposition of Unit VI was controlled by local structures and occurred on the hanging wall blocks of half grabens in a late rift to early sag phase. Deeper lake systems could develop within these zones of maximum subsidence, thereby providing a sequence of very fine-grained sediments with only minor fluvial influence.

- Unit VI is present on the flank of the Merino High and centrally in the St Clair Trough, and may also be developed within parts of the Tantanoola Trough and in the undrilled southern Penola Trough.

- Any basal Eumeralla lake systems developed within the St Clair Trough and the Tantanoola Trough were not connected.

- Unit VI is better developed in the eastern Otway Basin, where the Eumeralla Formation overall is more lacustrine-dominated.

Lake Basin Development:

- In the Otway Basin, the thickest lacustrine seals are likely to be developed within the syn-rift Laira Formation because of its deposition within a balanced-fill lake basin.

- The Eumeralla Formation sediments had a high fluvial influx due to its deposition in a late rift to sag phase, associated with an overfilled lake basin. Fluvial sandstones are more dominant within the upper Eumeralla Formation sediments as these were deposited in a late sag phase. The lower Eumeralla Formation was most likely deposited within a high sinuosity fluvial system, whereas the upper Eumeralla was associated with a high-energy fluvial environment.

Seal Evaluation:

- Seal capacity results are more sensitive to variations in interfacial tension than variations in contact angle. Whether the interfacial tension values are derived from the nomographs of Schowalter (1979) or Clinch (1996) has a negligible effect on calculated gas column heights. Samples derived from core give higher seal capacities than sidewall core and cuttings samples.

- High seal capacity lithologies are present within all of the investigated Eumeralla Formation intervals (Units VI to II). Calculated gas column heights range from 4 meters to 812 meters.

- The poorest sealing facies occur within the upper Eumeralla Formation (Units I, II, and III) because of its abundant sandstone interbeds providing possible pathways for hydrocarbon migration.

- The distal lacustrine Unit VI provides the best sealing facies, but is not developed basin wide.

Seal Prediction:

- There is a high risk of top seal fracturing in the Robe Trough, where coal beds are abundant within the lower Eumeralla Formation. Within the central Penola Trough, there is a relatively high risk of cross fault communication from sandstones being fault juxtaposed against sandstones.

- The best prospective Eumeralla seals are likely to be developed in the offshore troughs and in the area south of the Tartwaup Hingeline, where porosity and permeability are reduced through mechanical compaction and diagenesis.

- The onshore exploration risk associated with Eumeralla Formation seals has not been overcome by the recognition of Unit VI due to its limited thickness and distribution.

Chapter 8

Recommendations

8. RECOMMENDATIONS

- A comprehensive evaluation of seal integrity should be incorporated into the current Eumeralla Formation seal evaluation. Rock strength tests should be conducted on the lacustrine and floodplain sediments of Unit VI and Unit V to evaluate the risk of brittle failure. The high smectite-illite content and the presence of carbonaceous material may increase the risk of seal breach within these intervals.

- The depositional model proposed for Eumeralla Formation Unit VI (Chapter 5.6) suggests that a very good Eumeralla top seal may be developed in the undrilled, southern Penola Trough. Seismic data should be acquired and interpreted over this area to identify any potential structural traps.

- This Eumeralla Formation study was regional. The next step would be to evaluate sealing properties and the petroleum system on a prospect level, and test individual traps identified on seismic. With a good seismic resolution, the thickness and lateral extent of the lacustrine basal Eumeralla Formation may be determined. Better quality seismic data and 3D seismic may also identify with greater certainty the seismic signature of Eumeralla Unit V compared to Unit VI, thereby making it easier to determine where Unit VI is developed.

- Drilling within the southern Penola Trough would not only determine whether a very good seal is present at the base of the Eumeralla Formation, but also whether the Windermere Sandstone Member and the Katnook Sandstone are developed here. Drilling would also test the depositional model and theory of the best seal being developed against the footwall blocks of NW-SE trending faults, thereby reducing or increasing the prospectivity of the Tantanoola Trough.

- If prospects are identified, an investigation of fault displacement versus seal thickness should be conducted. Fault seal analysis is considered to be particularly important in the Penola Trough, where the sandy nature of the Eumeralla Formation is likely to cause juxtaposition problems. Acquisition of seismic data over the Tantanoola Trough would provide information on both structuring and facies development. Good Eumeralla seals are well developed in the Tantanoola Trough and seal risk is likely to be much lower here than in the Penola Trough. Structural development and fault displacement in the Tantanoola Trough should be investigated in order to evaluate whether seal thickness is sufficient to provide reliable top and lateral sealing.

- During this study, sampling was limited by sample availability. Now that general depositional and sequence stratigraphic models have been developed for the various Eumeralla Formation facies, it should be easier to define what intervals might require further analysis.

- Further research is also required at a small-scale level, studying the effects of mineralogy and diagenesis on seal capacity. This would be particularly valuable to the offshore Otway Basin troughs and the area south of the Tartwaup Hingeline where diagenesis may be the main factor influencing seal potential. The effects of smectite-illite transition on seal capacity should be investigated due to the Eumeralla Formation's high smectite content.

- Seismic sequence stratigraphy would be useful to test the lake basin type models proposed for the Eumeralla and the Laira formations by investigating key surfaces and stacking patterns. Facies associations occurring on a 1-10 meter scale in Eumeralla and Laira Formation cores should be compared to evaluate their different lake basin development. The structural evolution of the Otway Basin is also analogous to the Gabon and Cabinda Basins of the west coast of Africa. Parasequences and lake facies associations should be investigated here to evaluate how these deposits compare to the Otway Supergroup.