Chapter 1

Introduction

1. INTRODUCTION

1.1 Project Rationale

Fault and top seal leakage and CO_2 charge have been identified as the primary risks associated with Otway Basin traps (Boult 2002/03). The intensity of faulting within the basin, brought about by the development and superposition of successive tectonic events, provides a significant risk to trap integrity (Boult 2002/03). Prospective exploration plays have been identified within large parts of both the onshore and offshore Otway (Fig. 1.1). Onshore, the Pretty Hill Formation and the Katnook Sandstone are considered the most prospective reservoir facies, whereas the Waarre Sandstone and turbidite slope fan deposits represent the most prospective plays offshore (Figs 1.1, 1.2).

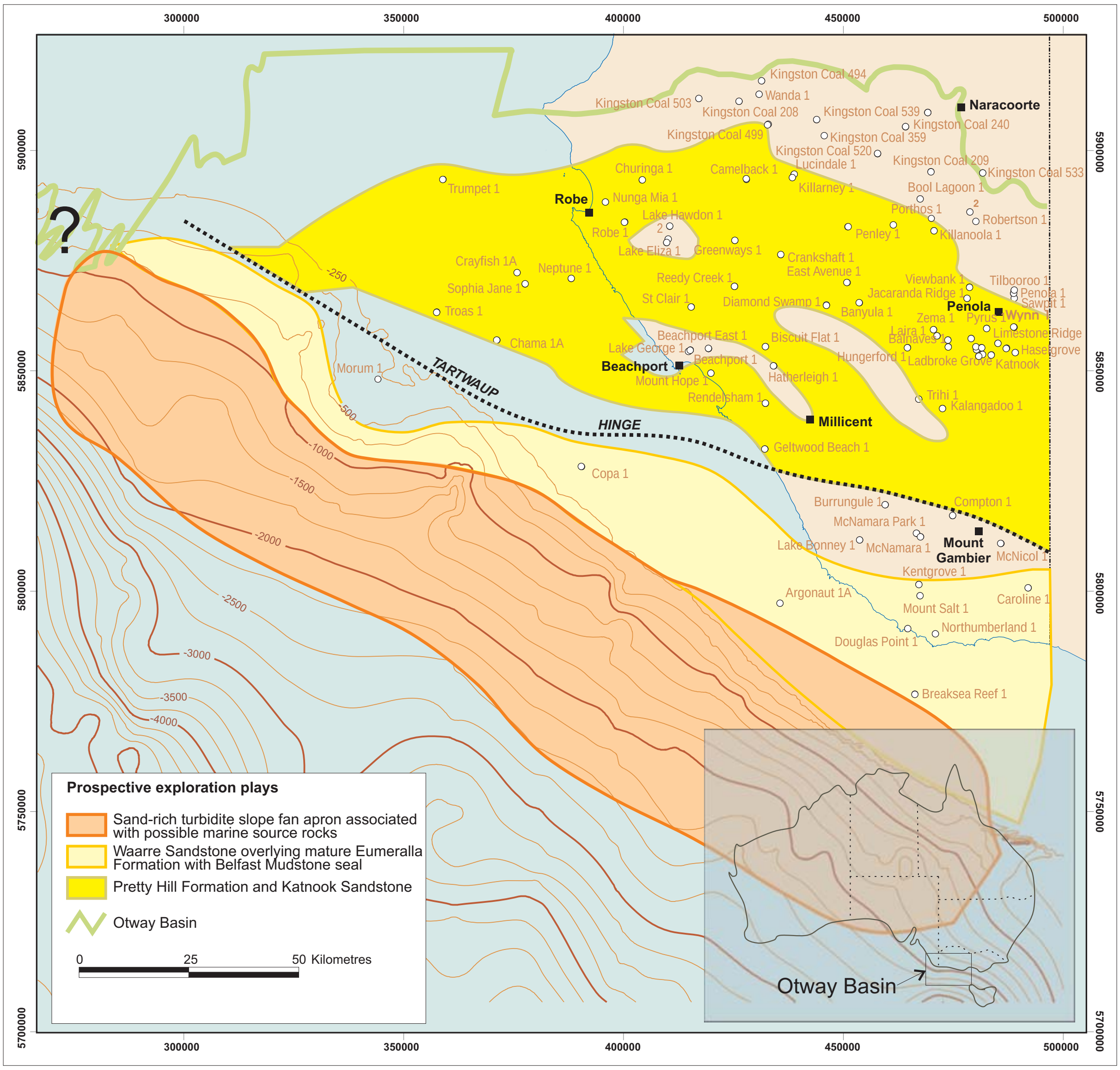

Figure 1.1 Play fairway map for the Otway Basin in South Australia (Boult 2002).

Regional sealing of Pretty Hill reservoirs is provided by the Laira Formation, a proven seal within the Crayfish Group (Fig. 1.2). Further upsection, fluvial-lacustrine sediments of the Aptian-Albian Eumeralla Formation represent a widespread seal developed throughout the basin. The Eumeralla Formation commonly overlies sandstones with good to excellent reservoir properties, such as the Katnook Sandstone and the Windermere Sandstone Member (Fig. 1.2). The Windermere Sandstone Member/Katnook Sandstone reservoir has had commercial gas production from Katnook-1 and a 2m column exists within Crankshaft-1 (Fig. 1.1) (Boult 2002/03). However, the thin hydrocarbon columns have resulted in water production problems (Boult 2002/03). Isopach maps suggest prospectivity is higher centrally in the Early Cretaceous troughs, where the sandstones are better developed (Boult 2002/03). Any hydrocarbon accumulations present within this reservoir interval would be dependant on the overlying Eumeralla Formation as a top seal. However, the Eumeralla Formation is generally considered a poor regional seal within the Otway Basin due to numerous sandstone interbeds. Despite the drilling of many prospects in the Penola Trough, only one minor gas accumulation with 20 meters column height has been discovered that relies on the Eumeralla Formation as the cap seal (Jones et al. 2000). The many sandstone interbeds are more likely to be fault juxtaposed and naturally interconnected compared to the more sporadically occurring sandstones of the Laira Formation seal (Jones et al. 2000).

The presence of a deep-water lacustrine facies at the base of the Eumeralla Formation was suggested based on palynology, lithology and seismic data (Boult 1996, Boult et al. 2002). This facies has been referred to as Eumeralla Formation Unit VI (Boult 1996). The geometry and distribution of Unit VI is unknown, and the interval has not been observed in core. Sandstone interbeds are likely to be less developed within a deeper lake environment, creating the potential for very good sealing intervals at the base of the Eumeralla Formation.

It is the premise of this study that potential new plays could open in the Otway Basin if the Eumeralla Formation can be shown to be a viable seal. Limited work has been conducted in the central parts of the South Australian Otway Basin, as the Penola Trough typically has been the focus of exploration and research. Onshore areas such as the eastern Robe Trough, the central Tantanoola Trough and areas close to the Victorian border remain poorly defined due to sparse seismic coverage (Jensen-Schmidt et al. 2002). The Tantanoola and Geltwood Beach Troughs are completely untested (Boult 2002/3) (Fig 1.3). The main area of interest for

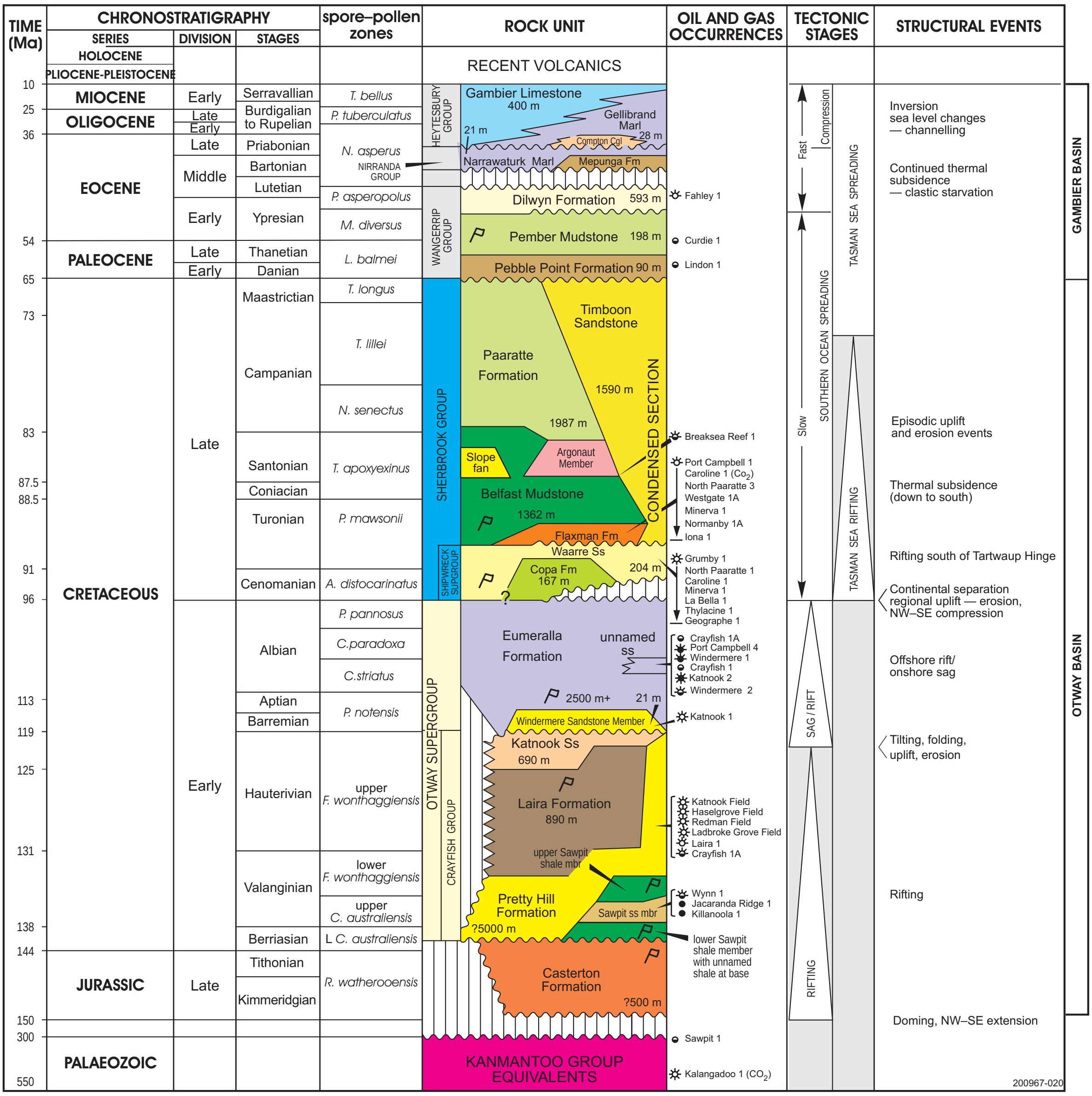

Figure 1.2 Stratigraphy of the Otway Basin in South Australia (Boult & Alexander 2002).

this study is the western Otway Basin, encompassing both the onshore and offshore South Australian Otway, as well as the western parts of the Victorian Otway Basin (Fig. 1.3).

1.2 Aims and Objectives

The primary aim of this project is to determine whether there are any good sealing intervals developed within the Eumeralla Formation, of sufficient thickness and lateral extent, to provide a reliable top seal for Katnook and Windermere Sandstone Member reservoirs. The objective is first of all to confirm the presence of a deep-lacustrine facies (Unit VI) at the base of the Eumeralla Formation. If present, the characteristics of Unit VI in terms of lithology, sedimentary and biogenic structures, porosity and cementation will be investigated in order to evaluate its sealing properties. The geometry of the various Eumeralla Formation Units will then be determined from seismic data and log correlation. A depositional model will be developed in order to describe and, if possible, predict the distribution of Unit VI throughout the explored and unexplored regions of the Otway Basin.

To improve the understanding of seal distribution and development a general sequence stratigraphic model will be devised for the Eumeralla Formation. Continental sequence stratigraphy is a valuable tool for predicting the distribution of reservoir, seal and source rock intervals in fluvial-lacustrine successions (Bohacs 2002; Lang et al. 2002a). By evaluating seal distribution in terms of changes in sediment input, base level and accommodation space, a better understanding of seal geometry and interconnectivity may be developed. Finally, the seal potential of the various Eumeralla Formation facies will be assessed in order to predict where within the Western Otway Basin good Eumeralla seals are likely to be developed.

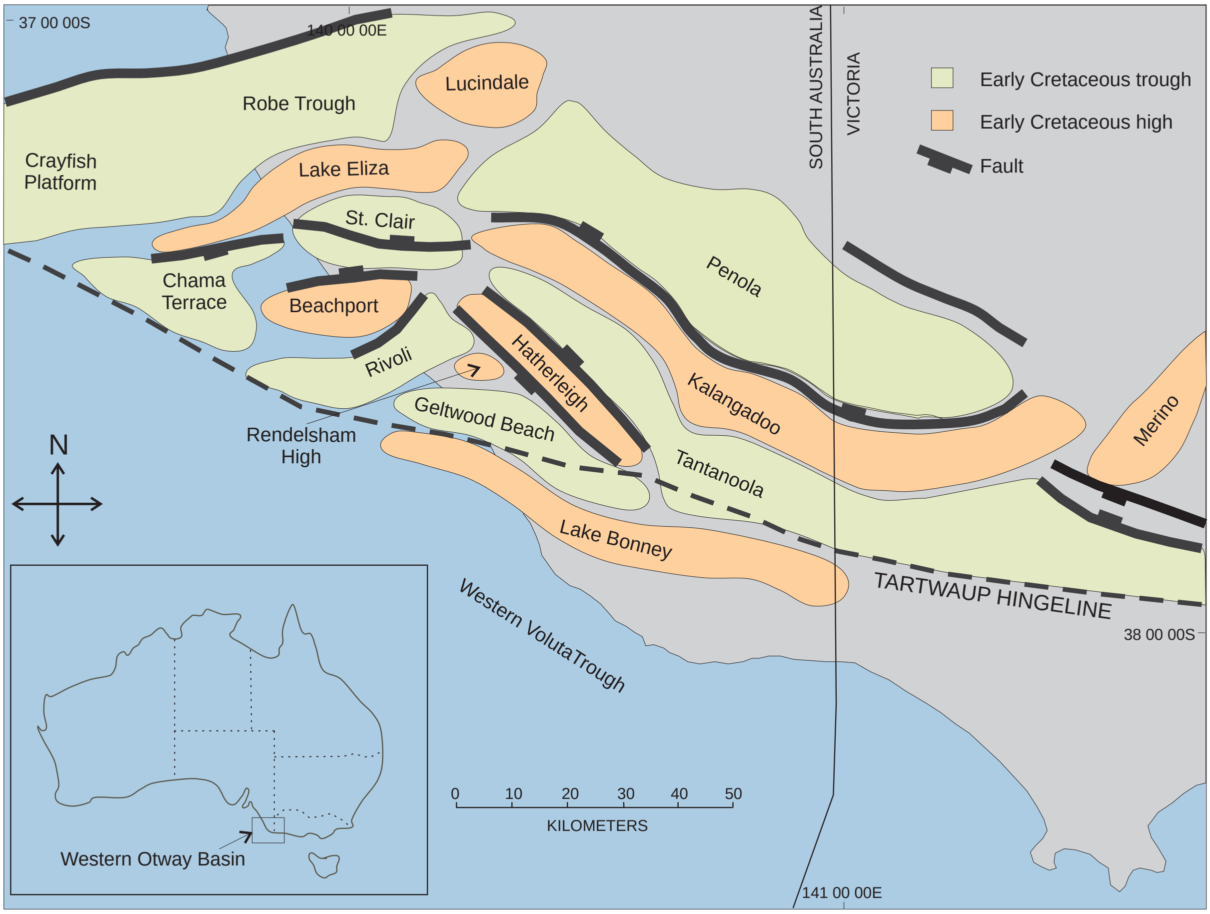

Figure 1.3 Study area and structural elements of the Otway Basin. Modified from Cockshell et al. (1995), Boult & Alexander (2002).

1.3 Otway Basin Exploration

All major discoveries in the Otway Basin have so far been gas accumulations (Fig. 1.4). Petroleum exploration in the basin commenced in 1882 with drilling at Alfred Flat near Salt Creek in South Australia. Drilling based on mapping of surface anticlinal structures in the early 1900s was unsuccessful, and the negative trend only changed after extensive seismic surveys were acquired by the Frome-Broken Hill Company Pty Ltd in 1958. Sub-commercial gas within the Late Cretaceous Waarre Sandstone was discovered onshore in Port Campbell-1 in 1959. An extensive offshore aeromagnetic survey acquired by the Frome-Broken Hill Company Pty Ltd in 1960 and 1961 defined the offshore extent of the basin (Geary & Reid 1998).

Shell Development and Esso Australia Pty Ltd. were the main explorers in the Otway Basin through the 1960s and 1970s, and were among the companies that moved exploration offshore following major petroleum discoveries in the adjacent Gippsland offshore basin (Sprigg 1985). However, the major companies departed the Otway Basin in the late 1970s declaring it to be non-productive. All offshore permits were surrendered and onshore permits were retained by small Australian companies (Sprigg 1985).

Thick porous and permeable sandstones at the base of the Lower Cretaceous sequence were discovered in Pretty Hill-1 in 1962, and soon became a prime exploration target. Alliance Oil discovered commercial CO_2 in the Late Cretaceous Waarre Sandstone when drilling Caroline-1 in 1967. In 1979, Beach Petroleum NL discovered commercial gas at North Paaratte in the Waarre Sandstone only three kilometres from the initial gas discovery at Port Campbell (Sprigg 1985). The discovery resulted in an upsurge of exploration activity involving seismic surveys and drilling. The first commercial gas discovery at Katnook-1 in 1987 was followed by the 1989 discovery of the Ladbroke Grove field (Harvey 1999).

Offshore, only minor gas flows were recorded between 1967 and 1993 from Pecten-1A in the east and Troas-1 in the western Otway Basin. In 1993, a drilling program conducted by BHP Petroleum and Bridge Oil Ltd resulted in the discovery of two large gas fields offshore from Port Campbell in western Victoria. La Bella-1 encountered gas in two Late Cretaceous sandstone intervals of the Shipwreck Group, sealed vertically and by cross-fault seal by Late Cretaceous claystones of the Sherbrook Group (Fig. 1.2) (Luxton et al. 1995). Minerva-1 also encountered gas within the Shipwreck Group, which was sealed by Late Cretaceous

Shipwreck Group silty claystones (Fig. 1.2). In 2001, Woodside had additional discoveries in offshore Otway following drilling of Geographe-1 and Thylacine-1 (Fig. 1.4). Both wells encountered over 200m gross gas columns, and later appraisal wells were successful. Santos and Strike Oil discovered gas within the Waarre Formation in Casino-1, offshore from Port Campbell, the following year (Fig. 1.4) (Williams 2002).

1.4 Prospectivity of the Eumeralla Formation

The La Bella and Minerva accumulations are the largest discoveries to date in the Otway Basin, and significantly enhanced the hydrocarbon prospectivity of the offshore Otway Basin (Luxton et al. 1995). Both gas accumulations were most likely sourced from coals and shales of the Early Cretaceous Eumeralla Formation (Luxton et al. 1995). These are the most prospective source rocks within the Cretaceous Otway section, but are mostly immature in the area north of the Tartwaup Hingeline (Fig. 1.3) (Boult 2002/03).

Reservoir sandstones are poorly developed in the predominantly fluvial-lacustrine sediments of the Eumeralla Formation, with the exception of the Heathfield Sandstone and localised Aptian sandstones providing secondary targets (Lavin 1997). Shows have been recognised in intra-Eumeralla quartz sandstones, but the sandstones tend to be thin and the reservoir quality is variable (Lavin 1997).

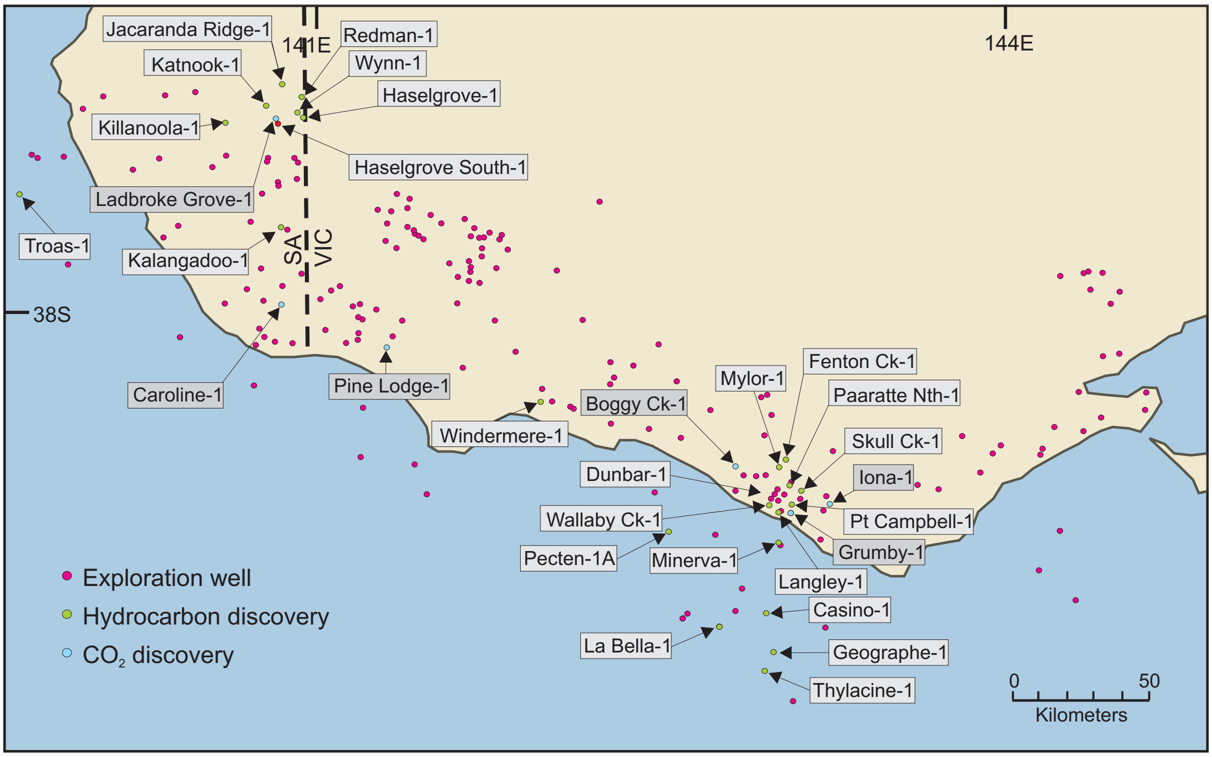

Figure 1.4 Exploration wells and discoveries in the Otway Basin. Dark gray well labels denote CO$_2$ discoveries. Modified from Mehin & Link (1994), Faulkner (2000).

Chapter 2

Geological Setting

2. GEOLOGICAL SETTING

2.1 Tectonic History

The Otway Basin forms part of the Australian Southern Rift System (ASRS), a divergent, passive continental margin extending 4000 km from the Perth Basin in Western Australia to the Sorrell Basin in Tasmania (Fig. 2.1) (Jensen-Schmidt et al. 2002). It is one of a series of Late Jurassic to Recent basins that developed on the southern margin of Australia in response to rifting, break-up and separation of the Australian and Antarctic plates. The basin covers approximately 150 000 square km, of which only 35% is onshore, and extends from Cape Jaffa in South Australia to the Mornington Peninsula in Victoria (O'Brien et al. 1994).

The onshore Otway Basin consists of mainly SE-trending Early Cretaceous troughs or half-grabens separated by basement highs (Figure 1.3) (O'Brien et al. 1994). The offshore part of the basin can be subdivided into three structural provinces, the Mussel Platform in the east, the centrally located Voluta Trough, and the ENE-trending Crayfish Platform in the west (Figs 1.3, 2.2) (O'Brien et al. 1994).

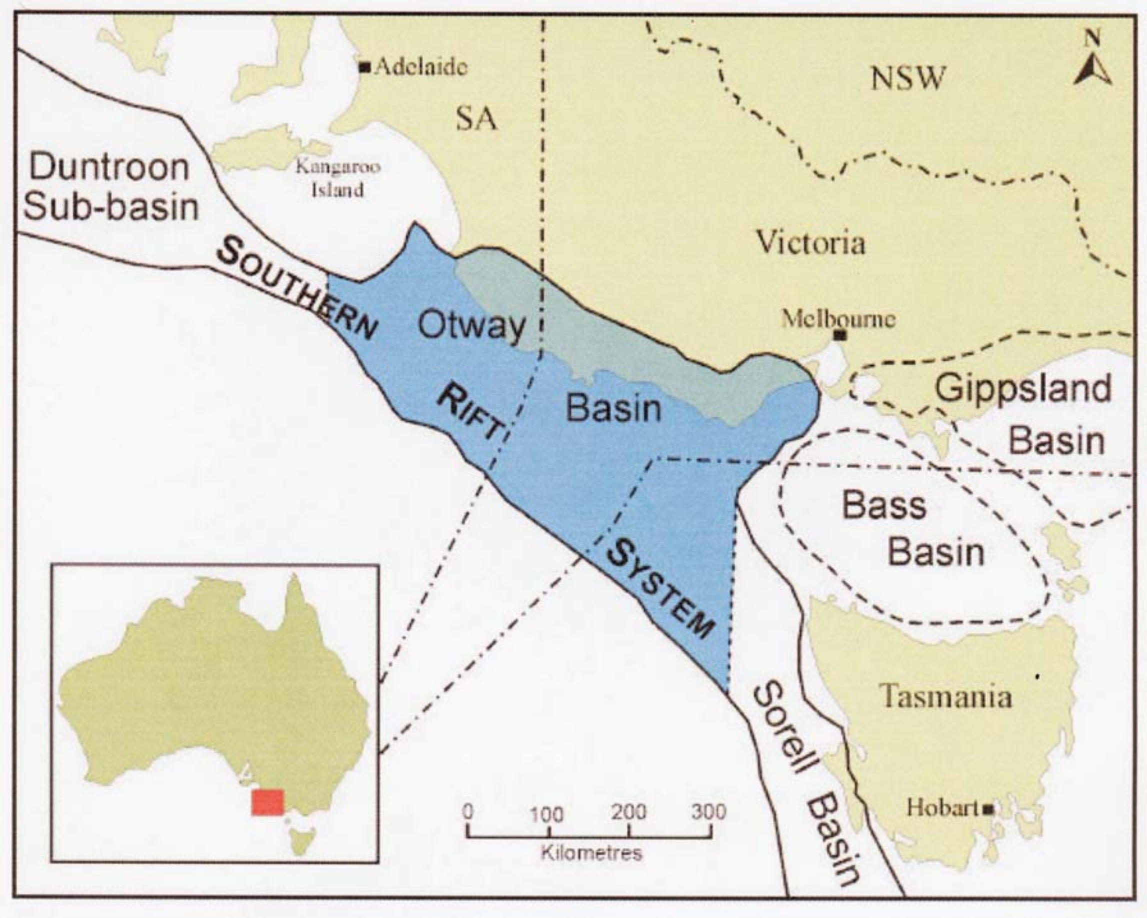

Figure 2.1 Location of the Otway Basin in the Australian Southern Rift System (Cockshell 1995, Pollock 2003).

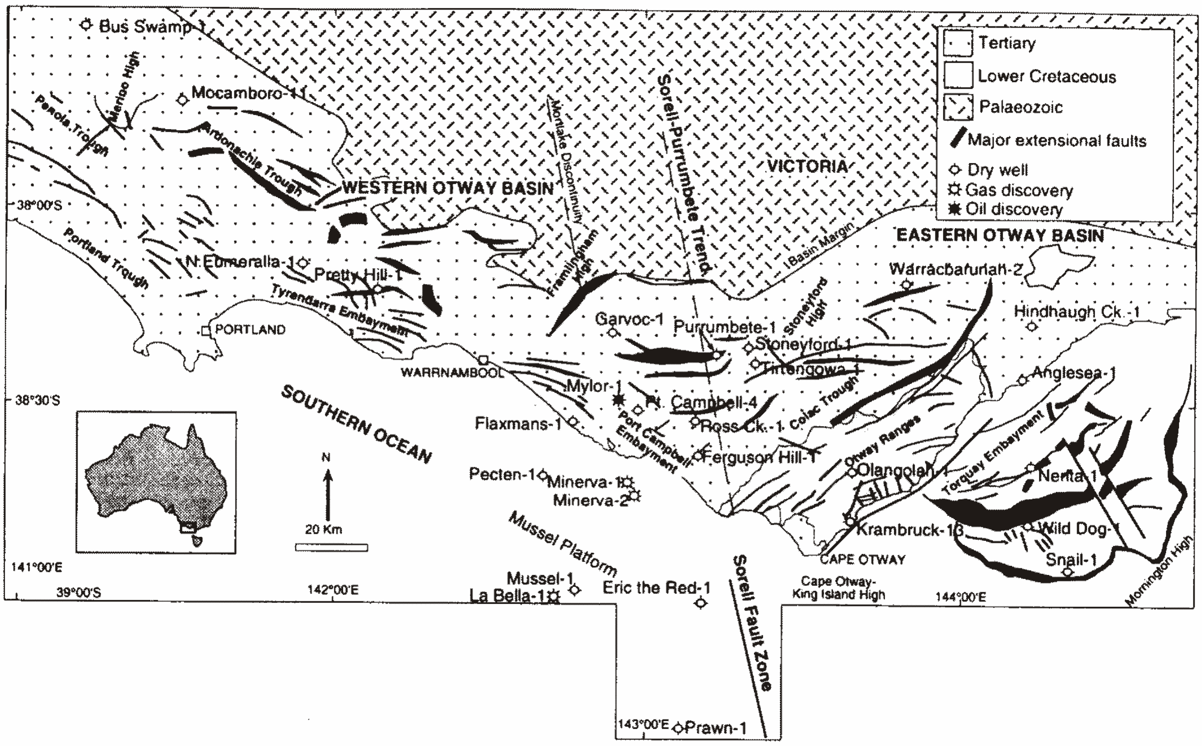

Figure 2.2 Location map of the Victorian Otway Basin showing the eastern extent of the basin, as well as the general division into a Western and Eastern Otway Basin (Cooper & Hill 1997).

2.1.1 BASEMENT

Pre-Mesozoic basement rocks consist of Palaeozoic metamorphic and igneous rocks and metasediments associated with the Kanmantoo fold belt of the Tasman Geosyncline (Fig. 1.2) (Yu 1988). The early to middle Cambrian metasediments are described as argillite or phyllite and outcrop on the eastern side of the Delamerian fold belt (Morton et al. 1995). Compressional deformation during the Cambro-Ordovician Delamerian Orogeny folded the sequence, and thrusting directed towards the craton produced imbricate structures and duplexes (Jenkins 1990). The Glenelg Metamorphic Complex, which outcrops along the basin’s northern margin in western Victoria, underwent low-grade metamorphism, deformation and bimodal magmatism (Morton et al. 1995). The geometry of the basement rocks strongly controls the sediment provenance and structural setting of the Otway Basin (Morton et al. 1995). Regional gravity and aeromagnetic data indicate N-S and NNW-SSE basement trends (O’Brien et al. 1994). The main basement faults trend N-S, and appear to have influenced the later development of the Mesozoic rift system (O’Brien et al. 1994). The Robe-Penola Trough forms a prominent east-west trend, interpreted to be an ancient basement feature (Fig. 1.3) (Morton et al. 1995).

2.1.2 LATE JURASSIC-EARLY CRETACEOUS RIFTING

Initial rifting of the southern margin was first thought to have developed in association with a right-lateral strike-slip coupling fault (Megallaa 1986). However, the currently favoured model is a two stage extensional development with an intermediate sag phase. An early stage, failed Late Jurassic-Early Cretaceous rift in the onshore Otway Basin was followed by a Late Cretaceous rift in the offshore western Otway Basin that resulted in Eocene breakup (Palmowski et al. 2001). The Late Jurassic-Early Cretaceous extension direction is debatable and has been interpreted by different workers as NNE-SSW (Etheridge et al. 1985; Veevers et al. 1991), NW-SE (Wilcox & Stagg 1990; O'Brien et al. 1994), NE-SW (Perincek & Cockshell 1995), and broadly N-S (Hill et al. 1995). Teasdale et al. (2002) preferred an initial NW-SE extension followed immediately by a NE-SW extension.

Rifting produced a number of west-northwest striking asymmetric half-grabens within the Palaeozoic sediments that are linked by complex transfer fault zones (Perincek & Cockshell 1995). These transfer zones cut across the main rift trends and, when active, produced localised warps, sags and ramps (Morton et al. 1995). Complex drainage patterns developed and changed over time as transfer zones were reactivated or new growth faults developed (Jensen-Schmidt et al. 2002). Half graben bounding growth faults continued to grow until the end of Aptian (Aburas & Boult 2001).

A change in the regional stress field at ~120 Ma led to differences in dip direction between the onshore and offshore parts of the Otway Basin (O'Brien et al. 1994). Onshore, in the Penola Trough, oblique extension (NW-SE extension direction) occurred from 150 to 120 Ma over a SW- to S-dipping master detachment ramp (O'Brien et al. 1994). This produced landward-dipping fault blocks during deposition of the Crayfish Group. The younger (Barremian to Maastrichtian) largely offshore section, however, formed during NNE-SSW extension from 120-96 Ma (O'Brien et al. 1994). This change in extensional direction was accompanied by fault reactivation, block rotation and uplift (O'Brien et al. 1994). Erosion of Crayfish Group sequences resulted in formation of the top Crayfish Group unconformity. The new stress regime produced almost purely extensional, seaward-dipping SE- to ESE-trending normal faults during deposition of the Eumeralla Formation and younger sediments (O'Brien et al. 1994). Sag dominated in the Aptian-Albian, and only subdued rifting occurred onshore.

A total extension of approximately 300 km took place along Australia's Southern Margin during early rifting, concurrent with deposition of the Crayfish Group (O'Brien et al. 1994). Only about 120 km of extension occurred during Eumeralla Formation deposition (O'Brien et al. 1994). Consequently, the Eumeralla Formation was deposited within less fault-controlled environments than the Crayfish Group (O'Brien et al. 1994).

The Australian and Antarctic plates are thought to have gone into minor compression prior to the deposition of the Eumeralla Formation, resulting in a major influx of volcanoclastic sediment into the Otway Basin (Hill et al. 1995). The volcanoclastic sediments most likely originated from an active volcanic arc along the Pacific margin in the east (Fig. 2.3), and have been interpreted to have, wholly or in part, driven basin subsidence (Hill et al. 1995). Gleadow & Duddy (1981) interpreted pulses of volcanism between 123 and 106 Ma using fission track dating. The sedimentation rate was able to balance the rate of subsidence and keep the graben system above sea level for at least 30 Ma (Duddy 1983).

Thermal sag and cessation of extensional and transfer fault movement in the Albian allowed a relatively uniform thickness of the upper Eumeralla Formation to be deposited across the basin (Aburas & Boult 2001). Eumeralla Formation deposition was followed by erosion of the upthrown fault blocks and peneplanation, particularly in the eastern Otway Basin (Perincek & Cockshell 1995).

2.1.3 LATE CRETACEOUS – TERIARY OCEANIC RIFT

Breakup and seafloor spreading commenced in the adjacent Bight Basin at approximately 83Ma (Sayers et al. 2001). Otway Basin breakup is younger than this and has been constrained to middle to upper Maastrichtian (Krassay pers. comm. Geoscience Australia 2004). The break-up passed south of Tasmania along the Sorell Fault and Tasman Fracture Zone, thereby leaving the onshore Otway, Bass and Gippsland Basins as parts of a failed rift (Fig. 2.3) (Hill et al. 1995). The initial opening of the Southern Ocean was slow, and coincided with post-rift subsidence and deposition of the marginal marine and deltaic sediments of the Sherbrook and Wangerrip Groups (Perincek & Cockshell 1995; Chantraprasert et al. 2001). In the eastern Otway Basin, lack of subsidence limited the accumulation of Upper Cretaceous sediments, which are proven reservoirs in the western Otway Basin and Gippsland Basin (Cooper & Hill 1997).

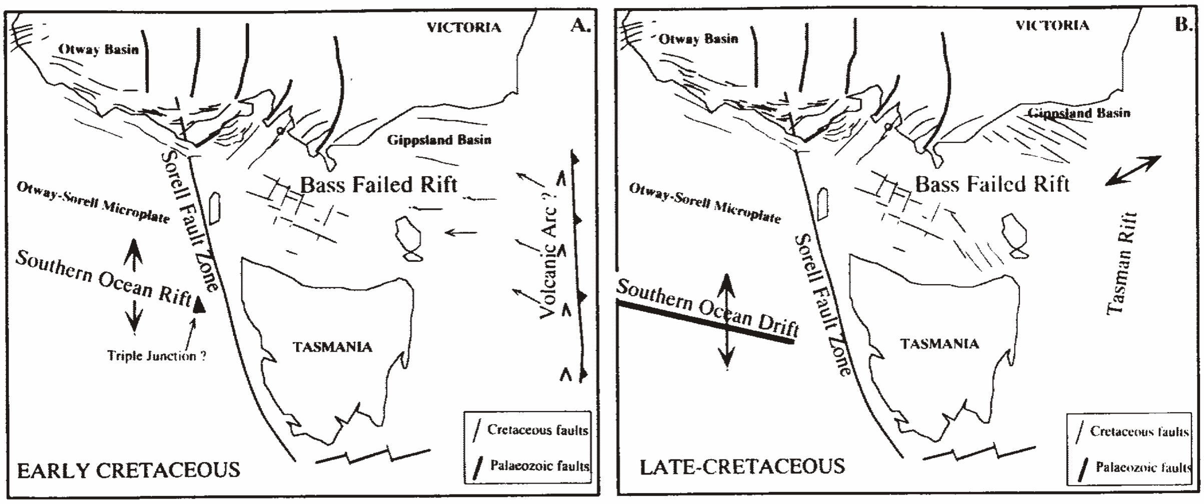

Figure 2.3 Schematic diagram showing: a) main structures developed during Early Cretaceous rifting. Sediment supply for the Eumeralla Formation may have been derived from a volcanic arc developed associated with a subduction zone in the east; b) Southern Ocean break-up passed south of Tasmania along the Sorell Fault zone and left the onshore Otway, Bass and Gippsland Basins as parts of a failed rift (Cooper & Hill 1997, Hill et al. 1995).

2.1.4 FAST SEAFLOOR SPREADING (Eocene-Recent)

Rapid drift between Australia and Antarctica commenced with the Eocene cessation of Tasman Sea spreading (Hill et al. 1995). The Australian plate moved rapidly northward following major plate reorganization at this time (Hill et al. 1995). Most of the outer continental margins collapsed into deepwater environments and widespread marine transgression occurred (Norvick & Smith 2001).

NW-SE compression during the Miocene to Recent caused anticlinal uplift and inversion of the NE-SW trending extensional faults (Perincek & Cockshell 1995; Hill et al. 1995). A NW-SE contemporary stress field has been determined from borehole breakout analysis (Hillis et al. 1995). The change in stress regime has been suggested to result from collision of the Indonesian microplates at the northern and eastern margins of Australia. Development of new Tertiary faults that propagated downwards resulted in a complex interaction with older, episodically reactivated rift faults (Lyon et al. In Press). In the Pliocene-Holocene, volcanic activity occurred along zones of weakness associated with reactivated fault systems (Perincek & Cockshell 1995).

2.2 Otway Basin Stratigraphy

The Otway Basin stratigraphic succession can be divided into five main packages or mega sequences (Lavin 1997). The Casterton Formation and the Crayfish Group represent a thick syn-rift package deposited in fault-controlled depocentres (Lavin 1997). The Eumeralla

Formation, the Sherbrook Group, the Wangerrip Group, and the Nirranda and Heytsbury Groups overlie this sequence (Fig. 1.2).

2.2.1 THE CRAYFISH GROUP

The Crayfish Group overlies lacustrine carbonaceous mudstones, sandstones and coals of the late Jurassic Casterton Formation (Chantraprasert et al. 2001). The Crayfish Group comprises the Pretty Hill Formation, the Laira Formation and the Katnook Sandstone (Figure 1.2). Poor biostratigraphic control, largely because of its rapid deposition in a non-marine environment, hinders correlation and further subdivision of the Crayfish Group (Lovibond et. al. 1995). Only three palynological zones are currently recognised within the sequence: the upper and lower *F. wonthaggiensis* zones and the upper *C. australiensis zone* (Morton et al. 1994).

The Pretty Hill Formation

The Pretty Hill Formation contains clasts from a number of different provinces (Harvey 1999), and is mineralogically complex (Morton et al. 1995). The sandstone is well sorted, quartzose, and generally has good porosity and permeability (Yu 1988). It mainly represents braided fluvial conditions (Morton et al. 1995). The sandstone contains varying proportions of siltstone interbeds, and shales occurring within the formation vary from floodplain to lacustrine origin (Lavin 1997).

The Laira Formation

The Laira Formation consists of siltstone and claystone, with minor fine-grained quartzose and feldspathic sandstone interbeds (Morton et al. 1995). The sandstones contain carbonaceous material with abundant plant fragments. Zones of high algal content (*Microfasta evansii*) near the top of the Laira Formation in the Katnook region have been interpreted to correspond to lake maximum, and reflect a general transition from a fluvial floodplain setting in the lower Laira Formation to a shallow lacustrine environment in the upper part (Morton et al. 1995). The base of the formation is transitional from low sinuosity fluvial facies of the Pretty Hill Formation (Morton et al. 1995).

The Katnook Sandstone

The Katnook Sandstone consists of cross-bedded arenites and carbonaceous silts deposited in a meandering to braided fluvial environment (Morton et al. 1995). It is difficult to distinguish these sediments from the sands of the underlying Pretty Hill Formation, especially where the

Laira Formation is thin (Morton et al. 1995). The top Crayfish unconformity represents the upper boundary of the Katnook Sandstone (Morton et al. 1995).

2.2.2 THE EUMERALLA FORMATION

The Eumeralla Formation is a chloritic, micaceous, carbonaceous, silty claystone with fine-grained feldspathic sandstone interbeds containing up to 53% volcanogenic fragments (Morton et al. 1995). The sediments were deposited in lacustrine and floodplain settings with interbedded channel sands and coal beds (Morton et al. 1995). The presence of Ostracoda indicates some marine influence in the upper part of the formation (Bao 2002).

The Windermere Sandstone Member

The Windermere Sandstone Member at the base of the Eumeralla Formation consists of fine-grained to pebbly sandstone with minor siltstone interbeds. The formation is commonly thin and widespread. Morton et al. (1995) interpreted the interval to represent a low sinuosity fluvial environment.

2.2.3 THE SHERBROOK GROUP

The Sherbrook Group (Turonian to Maastrichtian) consists largely of shale and medium to coarse sandstone horizons deposited as a marine to coastal plain succession (Morton et al. 1995). The Copa Formation overlies the Eumeralla Formation unconformably, and is likely to be developed in most areas south of the Tartwaup Hingeline although only limited well data are available (Morton et al. 1995). The Waarre and Flaxman Formations are shallow marine lower to upper-deltaic sediments deposited during Late Cretaceous transgression (Boyd & Gallagher 2001). The Belfast Mudstone consists of three distinct units deposited as inner to outer shelf sediments during open marine conditions. The Paaratte Formation and the Timboon Sandstone represents shallow-marine, deltaic and interdistributary sediments that prograded over the Belfast Mudstone (Boyd & Gallagher 2001).

2.2.4 THE WANGERRIP GROUP

The late Maastrichtian to early Middle Eocene Wangerrip Group represents post-rift transgressive/regressive clastic cycles (Lavin 1997). The unit is a progradational, deltaic to marine succession that extends across the Otway Basin. The sequence is similar to the underlying Sherbrook Group, and consists of a basal sandstone (the Pebble Point Formation) overlain by a distal deltaic mudstone (the Pember Mudstone) and deltaic sandstones and shales of the Dilwyn Formation (Laing et al. 1989, Mitchell 1997).

2.2.5 THE NIRRANDA AND HEYTESBURY GROUPS

The Wangerrip Group is overlain by carbonates and siliciclastics of the Eocene to Recent Nirranda and Heytesbury Groups. These sediments are dominated by limestones and marls deposited as a progradational succession in an open marine environment following late Eocene transgression (Lavin 1997, Mitchell 1997). The Nirranda Group generally grades upward into the carbonate sequence of the Heytesbury Group, which represents a second major marine transgression in the Oligocene to Miocene (Yu 1988).

2.3 Main Mesozoic Structural Elements

Five major Early Cretaceous Crayfish Group depocentres have been identified in South Australia, the Robe, Penola, Tantanoola, St Clair and Rivoli Troughs (listed in descending order of depth and lateral extent) (Fig. 1.3) (Cockshell et al. 1995). The troughs are areas where basement is deep, and are defined to the north and the south by major faults or basement highs (Jensen-Schmidt et al. 2002).

Robe Trough

The Robe Trough is the most dominant rift compartment and marks the western edge of the Otway Basin (Fig. 1.3) (Cockshell et al. 1995). The onshore portion of the ENE-trending trough is a full graben comprising two opposing half grabens with major bounding faults to the north (the Trumpet Fault) and to the south (the Lake Eliza Fault). The Trumpet fault has a basement throw of up to 6500 meters (Jensen-Schmidt et al. 2002). The Chama Terrace and the Crayfish Platform were previously referred to as subdivisions of the Robe Trough (Tupper et al. 1993), but relate to post-Crayfish Group structuring (Jensen-Schmidt et al. 2002).

Penola Trough

The NW-SE trending Penola Trough is bounded to the south by a major north-dipping fault system made up by a number of en echelon faults (Jensen-Schmidt et al. 2002). This has been referred to as the Kalangadoo Fault System (Cockshell et al. 1995), and marks the transition between the Penola Trough and the Kalangadoo High (Fig. 1.3). The trough contains in excess of 5000 meters of Crayfish Group sediments that thin and pinch out towards the north (Cockshell et al. 1995). The northeastern margin is defined by the Kanawinka Fault, and the basement high to the east of this fault system is referred to as the Merino High (Cockshell et al. 1995).

Tantanoola Trough

The Tantanoola Trough is poorly defined and is only penetrated by wells on its margin along the Kalangadoo High. A basement rise separates the western end of the Tantanoola Trough from the St Clair Trough, while to the east it is separated from the Ardonachie Trough by a Crayfish Group thin (Figs 1.3, 2.2) (Cockshell et al. 1995). Seismic data indicate the presence of about 3500 meters of Crayfish Group sediments in the west, adjacent to the Hatherleigh High (Jensen-Schmidt et al. 2002). The sequence is up to 4500 meters thick in Victoria, and is undefined in the central regions of the trough (Jensen-Schmidt et al. 2002).

St Clair Trough

The St Clair Trough is considered a western extension of the Penola Trough, with similar litho-stratigraphic sequences (Akbari 1992). The smaller, E-W trending trough is separated from the Penola and Tantanoola Troughs by basement saddles (Fig. 1.3) (Cockshell et al. 1995). The thickest Crayfish Group sequence has developed immediately north of the north-dipping St Clair Fault. A major N-S basement ramp separates the St Clair Trough from the much deeper Robe Trough towards the west (Cockshell et al. 1995).

Rivoli Trough

Beachport High separates the St Clair Trough from the NE-SW trending Rivoli Trough, located further towards the south (Fig. 1.3). The thickest sedimentary section is preserved adjacent to the Beachport South Fault (Jensen-Schmidt et al. 2002). Rapid thinning of sediments towards the southeast was partially caused by erosion after Crayfish Group deposition (Cockshell et al. 1995).

Tartwaup Hingeline

The Tartwaup Hingeline is a major structural feature in the South Australian Otway Basin that is aligned obliquely to the basin’s overall NW-SE structural grain (Fig. 1.3). It represents a set of en echelon faults, and the Eumeralla Formation, the Sherbrook Group and the Tertiary sequence thicken dramatically basin ward of this structure (Jensen-Schmidt et al. 2002).

Chapter 3

Methodology

3. METHODOLOGY

3.1 Database and Sampling

Wireline logs, palynology, 2D seismic data, sidewall cores and cuttings descriptions and conventional core provided the basis for interpreting facies and determining seal geometry. An integration of these data sets allowed a better understanding of the Eumeralla Formation facies to be developed despite the overall large well spacing in a structurally complex basin. The following sections provide a review of available data used for well correlations, as well as a brief outline of laboratory techniques and analysis performed.

3.1.1 SEISMIC DATA

Migrated 2D seismic data were interpreted for one offshore area covering parts of the Robe Trough and Chama Terrace, and two onshore areas over the St Clair Trough and an eastern extension of the Tantanoola Trough (Fig. 3.1). The seismic interpretation could not be tied between the various areas because of limited seismic coverage and problems with multiple misties between the different surveys. Seismic facies were determined by picking horizons on wireline logs and creating synthetic seismograms. The synthetic seismograms were created by calibrating the sonic log with checkshot data, where available, and using the calibrated sonic as the time-depth relationship. Minor editing of the original sonic log was needed in some wells. Wavelets were extracted statistically. Both structuring and sediment geometry were studied to assess the presence and character of Eumeralla Formation facies onshore and offshore.

3.1.2 PALYNOLOGY

The palynology of Morgan (1988, 1990, 1991, 1992, 1994) and Price (1995, 2000) was applied as these authors have done extensive work within the Otway Basin, thereby allowing a more consistent facies interpretation. Some complicating factors are associated with pre-1995 palynological data. Dettmann and Playford (1969) and Helby et al. (1987) attempted to produce palynological zonations valid for all of eastern Australia despite some key species having different ranges between the basins (Morgan et al. 1995). The base of the *C. hughesii* Zone, commonly associated with the lower Eumeralla Formation, was particularly problematic as different authors proposed different correlations. Helby et al. (1987) defined the *F. wonthaggiensis/C. hughesii* boundary based on the first appearance of *F. asymetricus*.

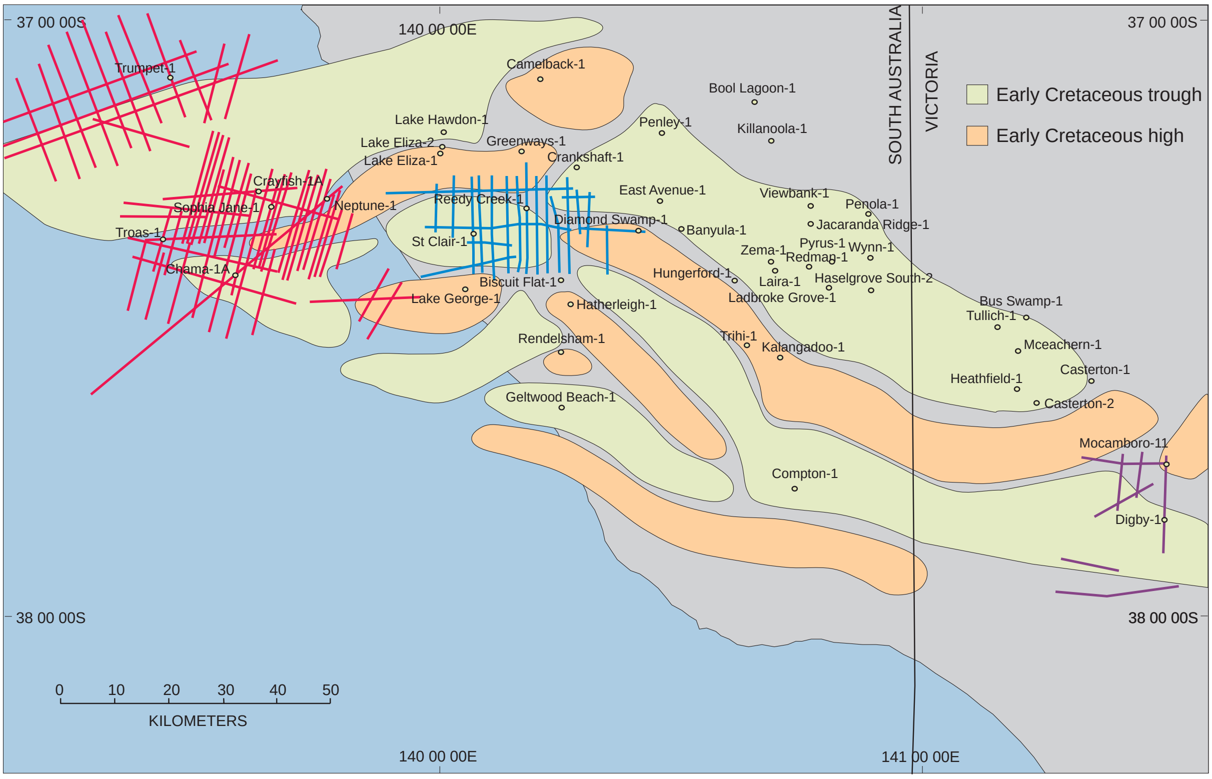

Figure 3.1 Wells and 2D seismic lines investigated as part of this study. The seismic lines are from seismic surveys oc90c and so94a (red), ho93, sc90 (blue) and omn93a (purple).

However, Morgan et al. (1995) argue that the first appearance of *P. notensis* is a better nomenclature and gave some stability to the Otway Basin palynostratigraphy by introducing the *P. notensis* Zone, thereby avoiding further use of the ambiguous *C. hughesii* Zone (Price 2000) (Fig. 3.2).

Despite extreme scarcity of some index taxa, the overall correlative framework within the Otway Basin is considered fair to good (Morgan et al. 1995). Zones in the Eumeralla Formation can be confidently identified with the possible exception of the boundary between the upper and lower *P. notensis* Zone (Morgan et al. 1995). This boundary is based on the youngest occurrence of the rare species *C. variabilis*, and is therefore of lower confidence (Morgan et al. 1995).

3.1.3 WIRELINE LOGS

Fifty-seven South Australian and Victorian wells were investigated, of which only fifty penetrated to the base of the Eumeralla Formation. Wireline log correlation between these wells is complicated by the volcanoclastic content of the Eumeralla Formation. The gamma

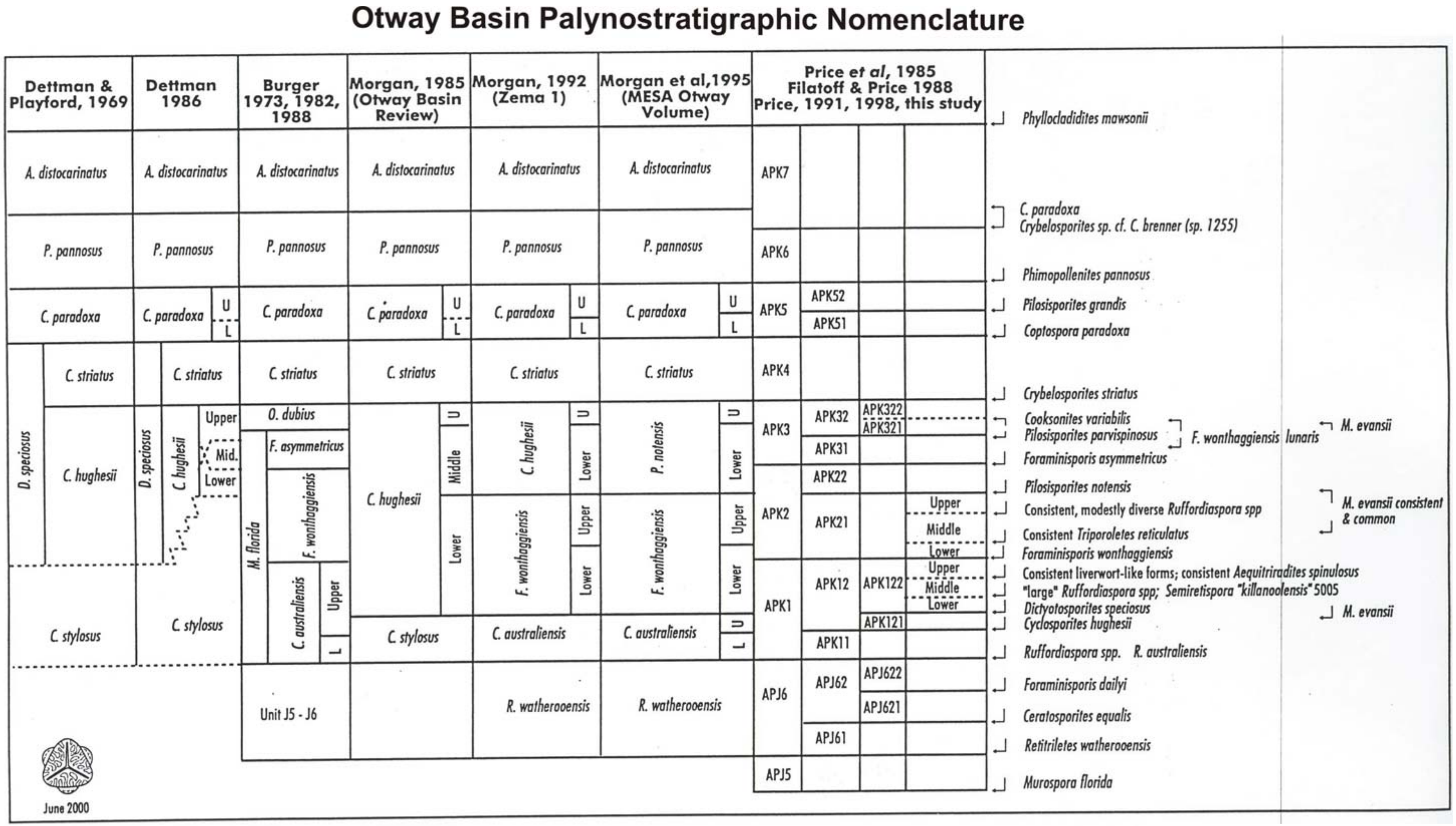

Figure 3.2 Palynostratigraphic nomenclature of the Otway Basin (Price 2000).

ray log is generally unable to identify the commonly occurring sandstone interbeds due to the sand’s “hot” signature caused by its high lithic and feldspar content (Montague 1989; Boult 1996). The SP log identifies Eumeralla sands with greater resolution than the gamma ray log (Jones et al. 2000), and was used together with sonic and density logs to determine facies. The scale on the SP log had to be customised for each individual well to allow a good display over the depth-interval of interest. For correlation purposes, all logs were flattened on top Eumeralla Formation, except for logs from the very deep Geltwood Beach-1 well. The main maximum flooding surface was not used because of the very variable character of the Eumeralla Formation between some wells. By flattening on top of the Eumeralla formation, variations in thickness and facies development between the structural troughs and highs could more easily be determined.

3.1.4 FORMATION TOPS

After several decades of exploration in the Otway Basin, the separate formations constituting the Crayfish Group have been identified in most wells throughout the basin. However, only the overall Crayfish Group has been identified in some wells. This study is primarily concerned with the Eumeralla Formation and the sedimentary sequence located above the Crayfish Unconformity, and no attempts were made to resolve the Crayfish Group lithostratigraphy.

Formation tops for the South Australian wells were taken from the PEPS-SA database of Primary Industries and Resources South Australia (PIRSA). No changes were made to these formation tops except for a change in the top Laira pick in Kalangadoo-1 (from 1891.59m to 1953m), as suggested by Boult (1996). This allows the Windermere Sandstone Member to be identified based on a SP log excursion at 1942 meters (Boult 1996).

For the Victorian wells, formation tops were taken from the database of the Department of Primary Industries in Victoria. The top Laira Formation in Digby-1 was lowered from 1102 meters to 1500 meters. Re-interpreted palynostratigraphy by Price (2000) suggests that the top Laira Formation in this well is significantly lower than previously assumed (Fig. 3.3). The new pick also corresponds well to lithology variations seen in sidewall cores (Fig. 3.3). The Laira Formation has a relatively high GR log signature and its top at 1500 meters corresponds to the main unconformity seen on seismic (Figs 3.3). The Windermere Sandstone Member can be picked based on a very distinct interval of low gamma ray log response and the occurrence of sandstone in sidewall cores (Fig. 3.3). A very similar log response is seen in Mocamboro-11, where the top Laira Formation was picked at 1000 meters.

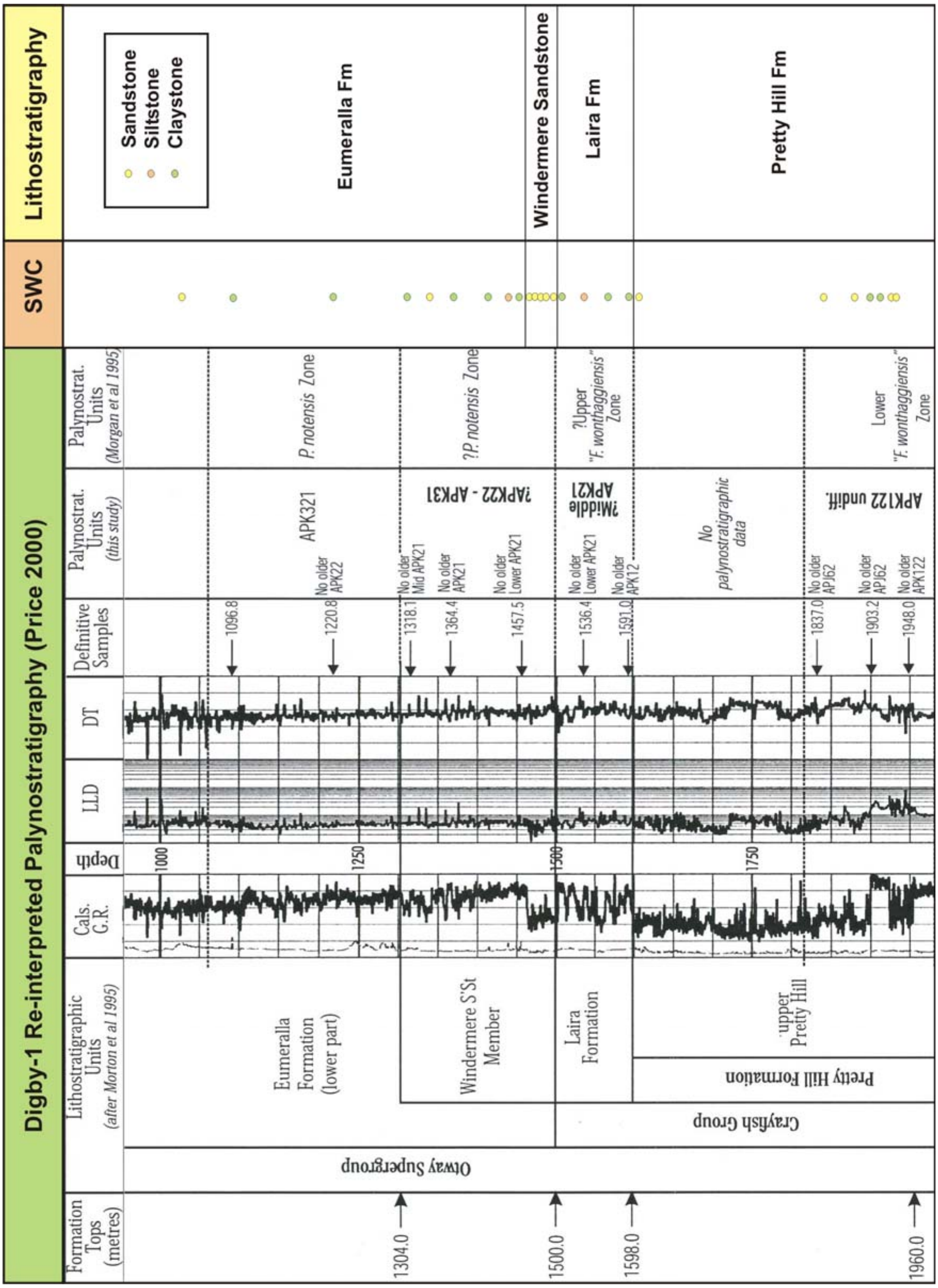

Figure 3.3 Changes made to formation tops in Digby-1 during this study based on log signature, lithological descriptions of sidewall cores and re-interpreted palynology by Price (2000).

3.1.5 CONVENTIONAL CORE

Cores from one offshore well (Crayfish-1A) and three onshore wells (Mocamboro-11, Kalangadoo-1 and Geltwood Beach-1) were photographed and sampled. Only core from the Victorian well, Mocamboro-11, was logged. This well provides core from the very basal Eumeralla Formation unit and is the only one of the above wells that was not logged by Montague (1989). Cores from all of the sampled wells are in relatively good condition, except for several porous and partly unlithified intervals that have disintegrated.

Only sidewall cores and cuttings samples were available from the remaining Otway Basin wells. Samples were collected from wells located south of the Penola Trough, where previous work is limited. Sampling was to a great extent governed by sample availability.

3.2 Laboratory Analysis

X-ray diffraction analysis and quantitative clay fraction analysis was conducted, and samples were prepared for scanning electron microscopy, mercury injection capillary pressure (MICP) analysis and the making of thin sections (Table 3.1). Sample preparation and methodology associated with MICP-analysis will be discussed in a later section (Chapter 6.2) as this forms part of the seal evaluation process.

3.2.1 X-RAY DIFFRACTION ANALYSIS

Standard X-ray diffraction analysis was conducted on core, sidewall core and cuttings samples. The samples were hand-crushed, diluted in deionised water, and then applied onto a slide washed in alcohol, and dried overnight. The XRD analysis was conducted at the University of Adelaide using a Phillips P W 1050 Diffractometer with a Cobalt Kα radiation source. The XRD plots were shifted to make the quartz-peak occur at 31.1 Angstrøm. Flared spikes occurred in some of the plots and were removed.

3.2.2 QUANTITATIVE CLAY FRACTION ANALYSIS

Quantitative clay fraction analysis was conducted on the two core samples that represent the finest claystone intervals of Mocamboro-11. Both bulk mineralogy and mineralogy of the <2μm particle size were analysed. Dewhurst et al. (2002) provides a detailed description of sample preparation and methodology used in this study.

3.2.3 SCANNING ELECTRON MICROSCOPY

Nine core samples, two sidewall cores and one cuttings sample were prepared for scanning electron microscopy. The core samples were cut both perpendicular and parallel to bedding. All samples were glued onto stubs, and coated with platinum after drying. A Philips XL30 FEGSEM with integrated EDAX DX4 Energy Dispersive X-ray Analyser was used to produce the images. A SEM has an electron gun at the top of an electron optical column and the beam is focused into a small spot that is scanned over the specimen in a raster pattern. The signal is electronically converted into an image that is used to assess the mineralogy and diagenesis of the sample.

3.2.4 THIN SECTION ANALYSIS

Thin sections were made from seven core samples from Mocamboro-11. The samples were first cut into 6-8mm thick slabs with a dry rock saw. The slides were impregnated with a blue resin to highlight porosity.

WELLNAME	DEPTH (m)	INTERVAL	SAMPLE TYPE	XRD	SEM	CLAY ANALYSIS	THIN-SECTION	MICP
Crayfish-1A	1005	Eum Unit II	Core	X				X
Crayfish-1A	1175	Eum Unit III	Core	X				X
Crayfish-1A	1528	Eum Unit V	Core	X				X
Diamond Swamp-1	1344-1350	Eum Unit V	CT	X				X
Diamond Swamp-1	1399-1402	Winderm Sst	CT	X				
Geltwood Beach-1	3016	Eum Unit IV	Core	X				X
Geltwood Beach-1	3725	Eum Unit V	Core	X				X
Kalangadoo-1	1194	Eum Unit II	Core	X				X
Kalangadoo-1	1364	Eum Unit II	Core	X				X
Kalangadoo-1	1869	Eum Unit V	Core	X				X
Lake Eliza-1	887-893	Eum Unit IV	CT	X				X
Lake Eliza-1	1060-1066	Eum Unit V	CT	X				X
Mocamboro-11	328	Eum Unit III	Core	X			X	X
Mocamboro-11	618	Eum Unit IV	Core	X	X		X	X
Mocamboro-11	651	Eum Unit V	Core				X	
Mocamboro-11	706	Eum Unit V	Core	X	X	X	X	X
Mocamboro-11	745	Eum Unit V	Core	X	X			X
Mocamboro-11	774-777	Eum Unit V	CT	X	X			
Mocamboro-11	835	Eum Unit V	Core		X			
Mocamboro-11	870	Eum Unit V	Core		X			
Mocamboro-11	871	Eum Unit V	Core	X	X		X	X
Mocamboro-11	907	Eum Unit VI	Core	X	X		X	X
Mocamboro-11	943	Eum Unit VI	Core	X	X	X		X
Mocamboro-11	981	Winderm Sst	Core	X	X		X	
Reedy Creek-1	1668	Eum Unit V	SWC	X				X
Reedy Creek-1	1679	Eum Unit V	SWC	X				X
Reedy Creek-1	1701	Eum Unit V	SWC	X	X			X
Sophia Jane-1	1515-1520	Eum Unit V	CT	X				X
St Clair-1	1924m	Eum Unit V	SWC	X				X
St Clair-1	1950m	Eum Unit VI	SWC	X	X			X
Troas-1	1030-1050	Eum Unit II	CT	X				X
Troas-1	2020-2030	Eum Unit IV	CT	X				X
Trumpet-1	877-896	Eum Unit III	CT	X				X
Trumpet-1	1268-1280	Eum Unit V	CT	X				X

Table 3.1 A summary showing the type of analysis performed on the various Eumeralla Formation samples.